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*Bachelor's Thesis*

# Electric grid planning of an isolated system in Isabela Island, Galapagos

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*AGRADECIMIENTOS*

A mi familia, especialmente a mis padres, por enseñarme a ver las cosas importantes y a luchar por lo que quiero.

A mis amigas por quererme tal y como soy.

A mi tutor David, por transmitirme esa pasión por aprender y a Miguel y David, por ayudarme con este trabajo y compartir buenos momentos.

**Resumen**

Este trabajo consiste en la planificación energética de un sistema aislado en la isla Isabela, Galápagos. Para entender el marco contextual en el que se desarrolla el proyecto, el trabajo abarca la evolución de la energía en las últimas décadas, las nuevas tecnologías energéticas, microrredes y las tendencias medioambientales. En esta transición hacia la sostenibilidad que el mundo está experimentando, Galápagos también juega su papel. Durante las últimas décadas, el crecimiento de la población y el turismo en las islas ha impulsado el crecimiento de la demanda, haciendo necesario que la capacidad instalada aumente a lo largo de los años. Galápagos toma parte en la lucha contra el cambio climático implementando proyectos de energías renovables en las diferentes islas y desarrollando políticas medioambientales contra la contaminación. Isabela es la única isla habitada en el archipiélago de Galápagos que todavía funciona completamente con combustibles fósiles, y eso es exactamente lo que le hace interesante para este estudio. Cinco escenarios son pronosticados y analizados con posibles futuros que pueden variar desde sistemas basados exclusivamente en combustibles fósiles hasta sistemas 100 % renovables. En esta planificación energética los diferentes sistemas son construidos con el software HOMER Pro, y simulados desde 2015 hasta 2035 en los años 0, 5, 10 y 20, años relevantes en la realización de una planificación energética. Todos los diferentes futuros que podrían tener lugar en la isla presentan sus ventajas y sus inconvenientes. A medida que la penetración renovable va aumentando, la cantidad de combustibles fósiles consumidos e importados y por lo tanto, las emisiones a la atmósfera se reducen, sin embargo conlleva que los precios se disparen.

**Abstract**

A grid planification of an isolated system in Isabela Island, Galapagos, is performed in this bachelor's thesis. An overview of global energy evolution in the last decades, mainstreams of energy production, microgrids and environmental trends are stated in order to get immersed in the contextual framework of the project. In this transition towards sustainability the world is going through, Galapagos plays a role too. For the last decades, population and tourism growth have boosted the demand and thus additional installed capacity will be needed in the upcoming years. Galapagos is fighting back climate change promoting decarbonization and implementing many renewable energy projects and environmental policies against pollution. Isabela is the only inhabitated island that is still powered completely by fossil fuels and that is exactly what makes it interesting for this study. Five different case scenarios are forecasted and analysed with possible futures that ranges from a completely non-renewable system to a 100 % renewable system. In this grid planning, the different scenarios are built with the software HOMER Pro and simulated from 2015 to 2035 in the years 0,5,10 and 20, relevant years in a grid planification. Analysing the results obtained, it can be seen that all the possibilities have advantages and disadvantages. As renewable energy penetration increases throughout the years, fuel imported and consumed and thus the emissions to the atomsphere decrease, however the price of the system increase considerably.

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# 1. Introduction

## 1.1. Objectives

The aim of this bachelor's thesis is to perform an electric planification of an isolated system in Galapagos Islands, Ecuador. Among all the islands that make up the archipelago, the selected one for this study is Isabela Island. Isabela is one of the four inhabitated islands, is the largest in extension but not the most populated one. The fact that Isabela's electric system is less developed than the others makes it interesting for this study. Developement and industrialization of the world has brought severe challenges of energy scarcity and climate change that requires strong meausures and global cooperation to fight back. The world is undergoing a transition towards sustainability and Galapagos is following that trend too. Ecuador's government is promoting decarbonisation especially in the transportation and energy sector, implementing policies and supporting renewable energy. Since 2008 many renewable energy projects have been implemented in Galapagos, however Isabela's electric system is still powered completely by fossil fuels. Isabela's current situation is ideal to perform a grid planification, where different scenarios that could take place in the island are going to be simulated and analysed in a time frame up to 2035. These scenarios cover possibilities from completely non-renewable to 100 % renewable systems. The study will show the way the Island is affected by each scenario in an electrical, economical and environmental points of view.

## 1.2. Structure and development

The structure of this thesis follows a deductive approach, that will allow the inmersion in the contextual framework of the Project. Section 1 presents the introduction, objectives, structure and softwares used . State of the art in Section 2, covers an overview of the Global energy situation, explaining briefly the evolution of energy in the last decades and the facts, reasons and needs that have boosted the transition towards sustainability and the shift away from fossil fuels. Once renewable energies are introduced as a part of the solution with environmental and economical advantages, the next subsection embrace distributed generation and systems as a way of integrate renewable energy in an easier and more efficient way. The following topic are microgrids. A microgrid is a smaller version of the grid composed of intterconected loads and distributed generation sources that can connect and disconnect from the main grid enabling a stand-alone operation mode. For the past few years this concept has been introduced as a way of providing secure and reliable energy to developing countries, islands and remote areas. Definition, attributes, components, types of microgrids, brief history as well as current statistics and data of projects and megawatts installed worldwide are given. The last subsection in the state of the art following the deductive approach covers the challenges that islands face compared to mainlands, regarding the quality, reliability and affordability of electricity. Besides, islands are said to be suitable scenarios to test innovative technologies and microgrids. Among all the islands in the world, Isabela in Galapagos is selected and analysed in section 3. An outline of the history and energy context allow to understand the goals and specific needs of the area. After that, it is focused on Isabela's development, current situation and trends. Sofware used, explanation of the simulations and projection of demand is covered in section 4. HOMER Pro is the program used to run the simulations and case scenarios and as we are forecasting possible future scenarios, a projection of the demand needs to be performed in order to see how the system and electrical needs will evolve with time. In section 5, Isabela's current and possible future case scenarios are simulated over a time frame up to year 2035 to foresee the advantages and disadvantages than can come along. Isabela's real data of demand and power system provided by ELECGALAPAGOS are introduced in HOMER Pro to perform the simulations. Although the future is uncertain, different possibilities ranging from a non-renewable system to completely renewable system are discussed. In section 6 a comparison of all the scenarios from economical and environmental points of view is performed and finally conclusions are stated in section 7.

## 1.3. Softwares

To develope this Project three main softwares are used: HOMER Pro, Excel and LaTeX. HOMER Pro, which acronym stands for Hybrid Optimization Model for Multiple Energy Resources, is an optimization software for distributed power systems. HOMER Pro is used to perform the simulations of the different case scenarios analysed in this bachelor's thesis. To perform calculations, such as the projection of the demand in subsection [4.3] , arrange and discuss the results obtained, tables and graphics are made with Excell. Finally LaTeX is the program used to write the document. LaTeX is a high-quality document preparation system, designed to write technical and scientific documentation. Taking advantage of those three Softwares this bachelor's thesis is developed.

# 2. State of the Art

## 2.1. Overview of Global Energy Situation

Energy is the master resource that boosts civilization progress. World's development has been and is still supported by natural resources, highlighting energy, that is considered as the main driver of economic growth. Due to the rapidly increasing demand, severe challenges of energy scarcity and climate change have appeared. [11]

Energy production market based on fossil fuel products started to decline especially after The Oil Crisis in 1973 and The Gulf War in 1991, events that caused the reduction of petroleum availability and growth of prices, resulting in a huge world wide inflation and an economic recesion. These facts gave rise to study alternative fuels and alternative energy production methods.[12]
Renewables are currently established around the world as popular sources of energy, and the trend is to evolve towards a 100 % renewable energy future.
According to [12], renewable energy potential largely exceeds all other forms of energy, and it is increasing rapidly due to several factors such as improved cost-competitiveness of technologies, orientated policy initiatives and increased awareness about energy security, environment and climate change.[1]

Although renewable energies are currently a mainstream and its use is rising rapidly, the share of renewables in global energy consumption is not growing that fast. This is due to the fact that in developed countries energy demand growth is slow while in developing countries the growth is fast, and fossil fuels play a significant role in meeting this rising demand. Besides in other regions of the world, development implies the swift away from traditional biomass for heating and cooking, reducing overall renewable energy share[13]. This is ilustrated in Figure 1 , which shows primary energy development from 2013 to 2015. In this figure it can be seen a huge primary energy supply coming from fossil fuels such as coal, oil and natural gas; and a small but growing share of renewable energy sources.

In this expansion trend of renewable energies that started years ago, 2015 has been a significant year, with the largest global capacity additions ever seen[1]. In 2015, events such as lowest-ever prices for renewable power long-term contracts, increased focus on energy storage systems and the COP 21 Climate Agreement played a significant role despite of an extreme decay of global fossil fuel prices.
This extraordinary year ended up with an historic Climate Change Agreement, COP 21, where 195 countries conforming the United Nations Framework Convention on Climate Change's (UNFCC), regardless their size or economic situation, signed an universal agreement to tackle climate change. The Agreement establishes a global warming goal of well below 2°C on pre-industrial levels. COP 21 is not the first agreement established to tackle climate change, however is the first one supported on voluntary mitigation contributions instead of country specific emissions targets, like the previous Kyoto Protocol. Moreover The Paris Agreement recog-

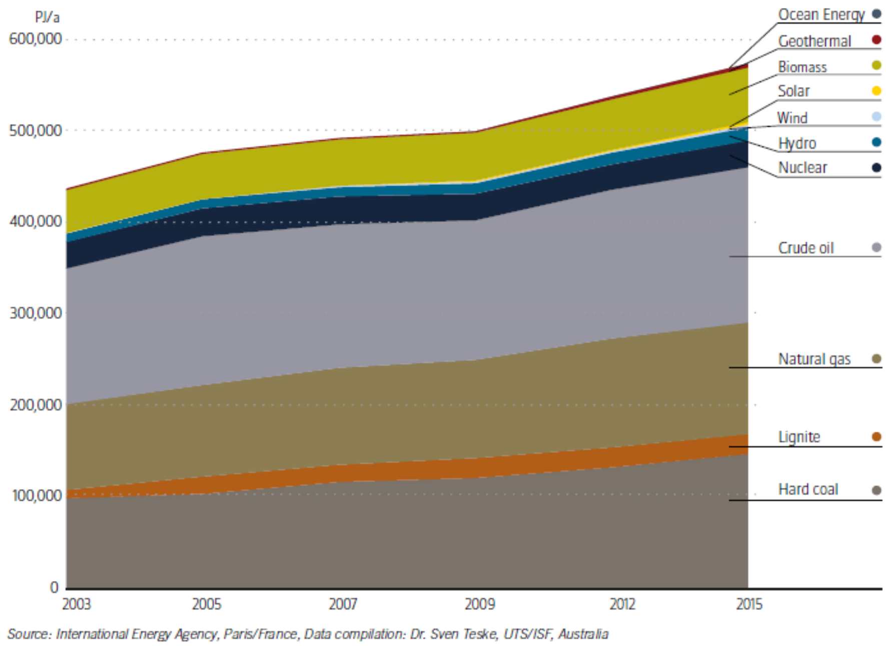


**Figure** 1: Worldwide Primary Energy Evolution 2003-2015[1]

nizes the different situation of countries and therefore different starting points, emphasizing in the implementation in accordance with the *"principle of common but differentiated responsibilities and respective capabilities"* which means that developed countries have to keep on taking the lead in mitigating climate change while supporting the decissions taken by developing countries. [14]

After all this events in 2015, there were signs that a global energy transition was on the way. Following year 2016, came with news such as the " 86 % of all new EU power installations were renewable energy sources, that China was becoming the country with the largest installed renewable capacity and that emerging economies and developing countries would start to take the lead on renewable energy investments, accounting for more than half of them". [15]. In year 2016 The journal SCIENTIFIC AMERICAN reported that " (...) the carbon dioxide we have already committed to the atmosphere has warmed the world about 1.8°F (1°C) since the start of the industrial revolution. This year is also set be the hottest year on record". Nowadays data from 2017 shows that the carbon dioxide concentration in the atmosphere reaches values over 400ppm, considerably high values that might be permanent. According to the experts, in order to avoid more catastrophic climate impact scenarios, is required to adopt stronger preventive measures, including the decarbonisation of the energy sector[15].

In order to provide reliable data and statistics of renewable energy capacity worldwide, documents from The International Renewable Energy Agency (IRENA) are analysed. As mentioned in [16]" The International Renewable Energy Agency (IRENA) is an intergovernmental organisation that supports countries in their transition to a sustainable energy future, and serves as the principal platform for international co-operation, and a repository of policy, technology, resource and financial knowledge on renewable energy. IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy, in the pursuit of sustainable development, energy access, energy security and low-carbon economic growth and prosperity". Figure 2 is created with data from document [16],*Renewable Capacity Statistics 2017*. This document provides and overview of main renewable energy types by country, over a period of time from 2007 to 2016.

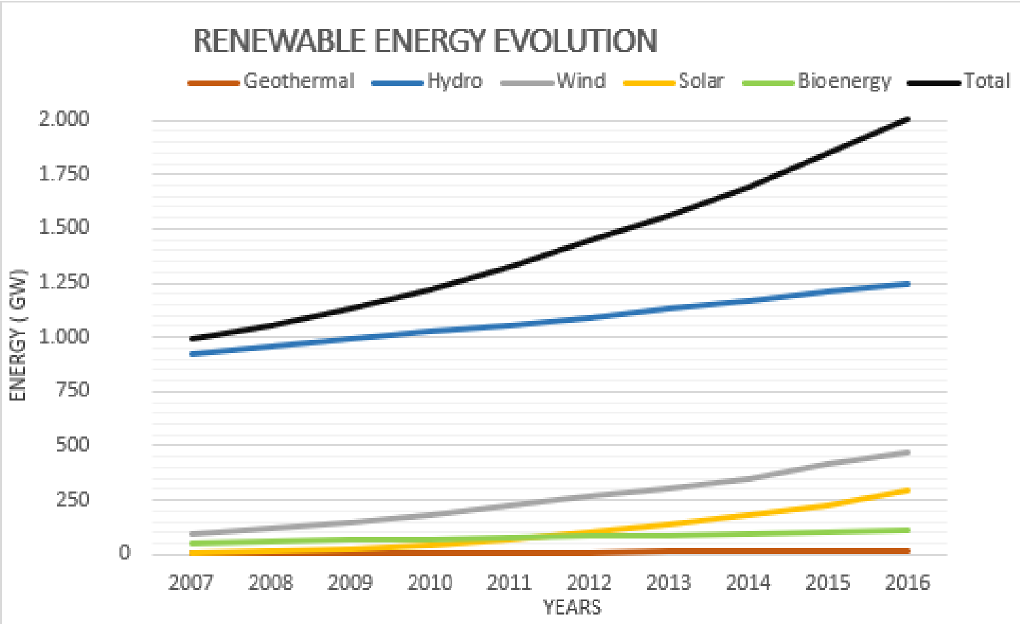


**Figure** 2: Worldwide Renewable Energy Capacity Evolution in GW 2007-2016

In Figure 2, different colors stand for the different renewable energy types, where the X-axis represents the time frame on years and the Y-axis the amount of energy in Gigawatts. Color *Black* line represents the *Total renewable energy*, accounting for a total value of 2.006 GW in 2016. In color *Blue* is represented the *Hydroelectric energy*, the type of renewable energy with more installed capacity and more MW produced. Next in the row are color *gray* representing *Wind energy* and color *yellow* representing *Solar energy* values, that rise over the years. Second to the last is color *Green*, that shows an almost constant evolution of *Bioenergy* and finally in color *Brown* the *Geothermal energy*, with considerably low values compared with the other types of energy.

## 2.2. Distributed generation and systems

"In this moment there is nearly 1.2 billion people around the world, approximately 17 % of the population, that live without electricity, the vast majority of whom are in Asia-Pacific region, Sub-Saharian Africa and Central-South America" [1]. This data is shown in figure 3 , where the lighter the blue color is, the less access to electricity the country has. [17].

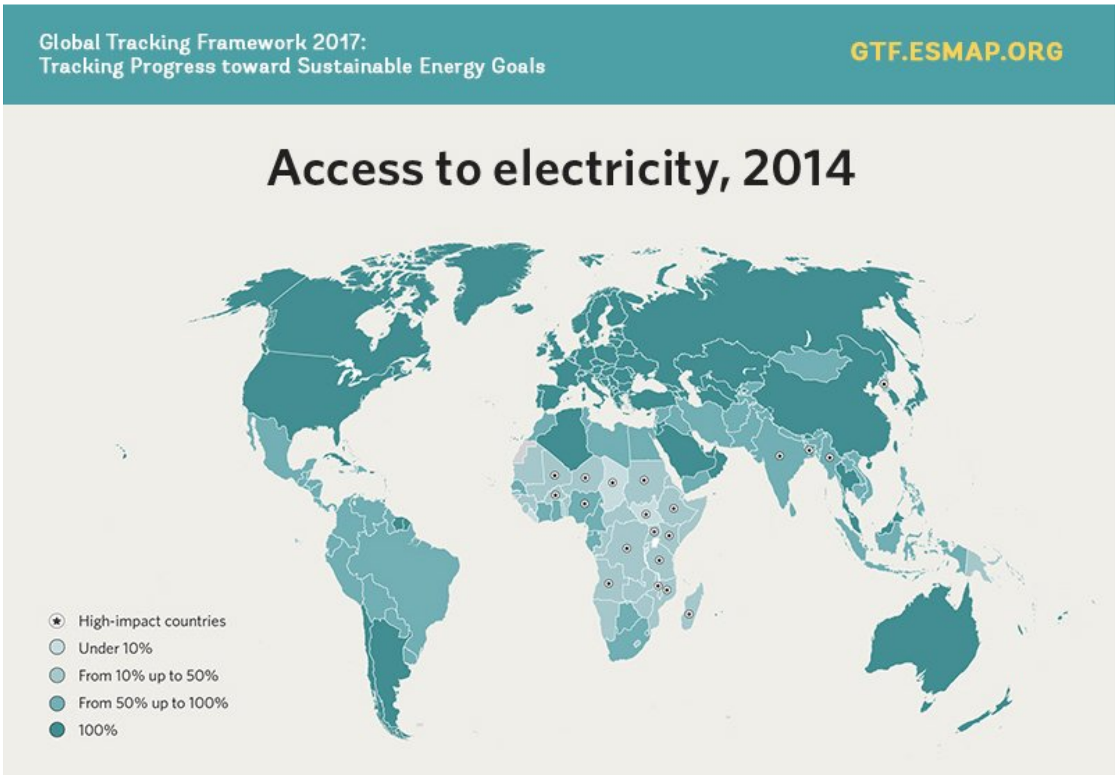


**Figure** 3: Global access to electricity per country [2]

To achieve sustainable energy development is required to eradicate energy poverty. Access to electricity promote economic growth, employment opportunities and social services such as education and healthcare[18]. In many rural areas of developing countries as well as some urban slums, build the connections to main electric grids are costly and sometimes inconceivable[1]. In this context, distributed generation plays a significant role. Although there is no consensus on the exact definition of distributed generation (DG), a good definition is the following: "DG is any source of electric power of limited capacity, directly connected to the power system distribution network where it is consumed by the end users". DG keeps on incresing in the power sector due to different factors:[19]

1. Reliability, especially in areas affected by natural disasters.
2. Increased power quality
3. Power loss reduction in the transmission and distribution levels.
4. Lower investment costs than traditional power plants due to their smaller size and lack of infrastructure.
5. Can provide power even in areas where convencional grid is not an option

6. Integration of renewable resources and therefore reduction in carbon dioxide emissions.

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As mentioned above, one of the most important attractions of distributed systems is the integration of renewable resources, such as wind, solar, hydro or biomass, that allow to produce power with minimum greenhouse-gas emissions. These systems are called distributed renewable energy systems (DRE).
As mentioned in [13], DRE systems can provide electricity for heating, cooking, lightning, communication and small businesses. DRE systems can serve as a complement to currently centralised energy generation systems or as a substitute. There are three categories of energy access technology designs:

1. **Stand-alone isolated systems** that provide power generation and residential needs, at the household level.

2. **Microgrid systems** that are able to supply power to entire communities.

3. **Grid-based electrification**, where the grid is extended to urban slums and peri-urban areas.

Each of the designs metioned above has advantages and drawbacks. On the one hand advantages of more centralised models include a higher suitability for industrial use and highly populated areas as well as, generally, lower cost per kW of energy. On the other hand, advantages of more distributed designs include lower losses in the transmission and distribution levels, suitability for small and remote communities and thus favouring local growth and security of supply. Besides, DRE systems have benefited from trends of decreasing system sizes and improved cost-competitiveness.[1]

According to recently available data, around 26 million households (or 100 million people) worldwide are powered through DRE systems. Among those DRE systems, around 20 million households are served through solar systems, 5 million households through minigrids ( usually powered by microhydro), and 0.8 million households through small-scale wind turbines. Markets for DRE systems are rapidly growing, and already achieving high market penetration in some countries. [1]

## 2.3. Microgrids

Traditional models of centralised generation are undergoing a transition towards smart decentralised models with distributed renewable generation and energy storage systems. This future smart decentralised model has the ability to reduce pollution and to increase the efficiency and reliability of the system. Nevertheless, the attributted intermittency of renewable energy and bidirectional power flows, create challenges in the power network. Microgrid systems were introduced to manage those challenges and assure network power quality and stability.[20]

### 2.3.1. Definition

According to [21], the most commonly used definition for microgrid is the one developed by the Department of Energy Microgrid Exchange Group: *"A microgrid is a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected and island-mode"*.
In this microgrid definition, two different parts should be highlighted:

1. **Single controllable load** . A microgrid has the ability to provide energy to interconnected loads in a controlled way that enables the microgrid system to be seen as a single controllable load to the eyes of the upstream power system it interconnects to, providing a flexible interface between the microgrid and the grid.

2. **Parallel and islanded operation mode**. A microgrid system is able to operate either parallel or islanded from the power system it interconnects to, providing unique services to the microgrid loads such as increased power quality and reliability; highlighting the ability to provide energy to the microgrid critical loads during a grid outage.

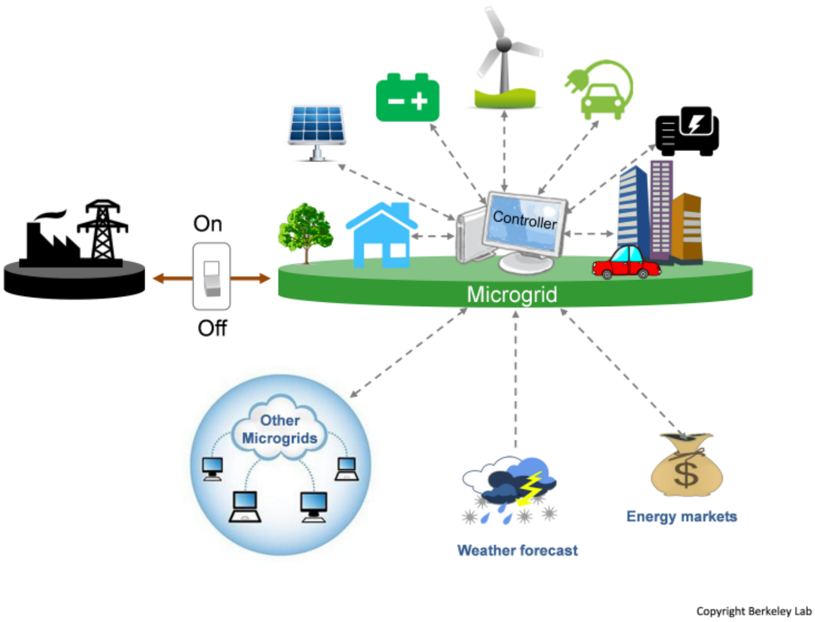



**Figure** 4: Microgrid Scheme[3]

Microgrids can connect to the main grid through the point of common coupling (PCC), that behaves like a switch that allows the connection and disconnection from the grid, figure 4 .

### 2.3.2. Attributes

Microgrids present many attributes such as: [22]

1. **Reliability and flexibility**: Microgrid systems are designed to provide uninterrumped power and to balance changing load demands, working either grid-connected or isolated.

2. **Autonomy**: Generation, storage and loads balance out voltage and frequency in an autonomous way.

3. **Resilient**: Microgrids can generate, distribute and control power independently from the grid, providing stability in case of black outs or natural disasters.

4. **Flexibility and scalability**: Expansion either in generation and/or consumption is easily performed adding devices in a parallel and modular manner. A diverse mix of renewable and fossil fuels can be introduced due to the fact that they are technology neutral.

5. **Secure sources**: Microgrids are powered with many distributed small generation systems connected to the distribution bus, providing redundancy and security of supply to the system.

6. **Optimized systems**: Taking advantage of different advanced control softwares, an optimization of the power demanded and costs can be performed.

7. **Storage and renewable energy integration**: These systems allow the integration of renewable energies and energy storage systems, reducing the carbon dioxide emission to the atmosphere.

### 2.3.3. Infrastructure and Components of a microgrid

A microgrid is made up of multiple interacting components located in a defined area. The components are connected and monitored trough advanced control systems to perfectly meet the requirements and needs of the area it is serving to. In figure 5 the main components of a microgrid are shown, however components may vary among microgrids depending on the specific requirements needed. Main components are the following:[4]

**The utility grid**
Microgrids have the ability to work either connected or disconnected from the main grid. Through the *Point of Common Coupling (PCC)*, that is the electrical connection point between the microgrid and the utility grid, located at the low-voltage bus of the substation transformer, the required operation mode is chosen,.

**Controllable loads**
Microgrids are designed to meet both electrical and thermical loads. Among the different loads found in a microgrid, some of them are considered to be critical

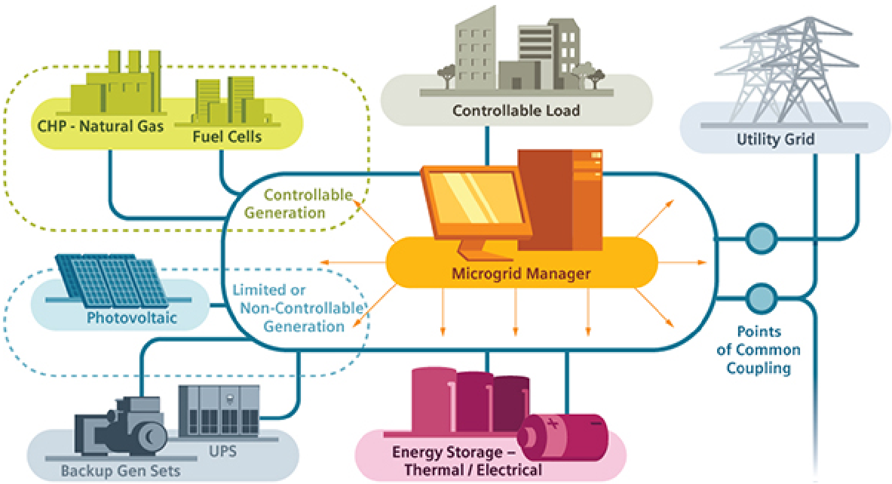



**Figure** 5: Typical components of a microgrid [4]

ones, thus they should always be prioritized. The non-priority loads can be used to provide control strategies such as demand side management, load shedding or peak shifting.

**Distributed Generation**

Distributed generation systems are usually connected to the low voltage or medium voltage levels, connected to different points of the microgrid and can be divided into two groups.

1. **Controllable Generation**
   Controllable generation systems are those that can be started when required in order to provide stable and necessary levels of voltage and frequency to the system. These generators are fed with nonrenewable fossil-fuel energy sources including biogas, fuel cells, gas turbines engines.

2. **Limited or noncontrollable generation**
   This kind of generation includes either renewable energy systems and backup generators, that can supply only a certain amount of power, and in the case of renewable systems, those are subjected to suitable environmental conditions. Among renewable energy sources, solar PV systems and wind turbines are commonly found in microgrids.

**Energy Storage Systems**

Allow to keep the power always available even if the environmental conditions are not suitable to power production. Energy storage can be both electrical and thermical systems. Batteries, thermal storage, flywheels and ultracapacitors are commonly used devices.However large scale storage systems have a high initial cost, therefore the most common technoly used are the batteries, especially in remote microgrids.

**Power management and control systems**

The power management system is the one on charge to transfer the electricity to the different consuming loads. Electricity usually interact with the storage components of the microgrid to balance the supply and demand loads.

### 2.3.4. Types of microgrids

According to [23] and [24], four key types of microgrids can be distinguised:

1. Institutional Microgrids: Are those located in an specific institution area, such as industrial parks, campus or hospitals, where both loads and generation systems belong to the same owner. These microgrids are leading the market due to their easier management and the fact that they fit in our current technology and regulatory structure. As said in [23] , scales ranges from 4 MW to more than 40 MW.

2. Remote or Islanded Microgrids: These type are always working in an off-grid mode, with non-existing possibility of connecting to the main grid due to their location, usually in remote villages, islands or peri-urban areas not reached by the utility grid. Usually powered with distributed renewable energy or back up generators, are generally the only source of energy for that location. According to recent studies, this category represent the largest number of current deployments of all microgrids.

3. Utility or Community Microgrids: The main feature of this type of microgrids is the incorporation of a segment of the main grid infrastructure, being different from a regulatory and business point of view.

4. Military Base Microgrid: These microgrids are deployed to protect military facilities from physical and cyber threats while assuring uninterrumped and reliable power. Physical and Cyber security imply that the circuit breakers and management controls are protected from outside tampering.

### 2.3.5. Currently existing microgrids

Although microgrids seem to be a new and revolutionary concept, they actually have a long history already. First microgrid was developed by Thomas Edison in the Manhatan Pearl Street Station, dating back to 1882. The system he designed in this station would perfectly match the microgrid definition. Edison's facility was small and self-contained, powered by six generators connected to the distribution level and included batteries for storage. By year 1886, there were 58 direct current microgrids installed by Edison's company. [22]
In the years that followed, the electric industry evolved to a centralized state-regulated markets, creating standards for current electric grid. Nevertheless, recent trends are breaking down the standars for generation-distribution grids, shifting back to decentralized microgrid systems and therefore revolutioning the markets. As mentioned in [25] "the first modern industrial microgrid was constructed in 1955, a 64 MW facility at the Whitling Refinery in Indiana, United States". Markets in microgrids are growing fast, technologies are improving and advantages are getting more and more noticeable. In order to understand the current situation of microgrids worldwide, two analysis are going to be performed:

### Analysis 1: Top contries by microgrid capacity and projects

This analysis is performed according to Figure 6, that presents a ranking of the *Top 10 countries by microgrid capacity and projects* with data from Navigant Report World Markets, 2016.[5]
In the top possition of the ranking is located United States, who is leading the microgrids' market both in Megawatts installed and number of projects. As we can see, in 2016 there were already 5.853,3 MW installed and 736 projects, a number considerably much bigger than the other countries. In order to understand this huge difference some facts have to be remarked:

1. First of all it must be noticed that U.S has been one of the pioneers and researchers in microgrids functioning and technologies.

2. Secondly, regulation framework and policies, especially after the election of Barack Obama for President in 2008, provided funds and supported microgrids development and implementation.[26]

3. Last but not least, the environmental unstability and natural dissasters commonly in the U.S fostered the necessity of more microgrid to increase reliability and security of supply in case of emergency, especially to critical loads such as hospitals.

| TOP 10 COUNTRIES BY MICROGRID CAPACITY AND PROJECTS | | | | |
|---|---|---|---|---|
| RANK | COUNTRY BY CAPACITY | MW | COUNTRY BY PROYECTS | PROJECTS |
| 1 | United States | 5853,3 | United States | 736 |
| 2 | China | 4267,9 | India | 171 |
| 3 | Russia | 816,9 | Canada | 132 |
| 4 | Canada | 778,1 | Australia | 43 |
| 5 | Australia | 694,4 | Japan | 35 |
| 6 | Indonesia | 528,9 | Spain | 33 |
| 7 | India | 351 | China | 31 |
| 8 | Denmark | 309,3 | Malaysia | 27 |
| 9 | France | 258,6 | Indonesia | 25 |
| 10 | Haiti | 256,1 | France | 16 |
| | Other | 1485,2 | Other | 319 |
| TOTAL | | 14114,6 | | 1249 |

**Figure** 6: Top 10 Countries by Microgrid Capacity and Projects, World Markets 2016[5]

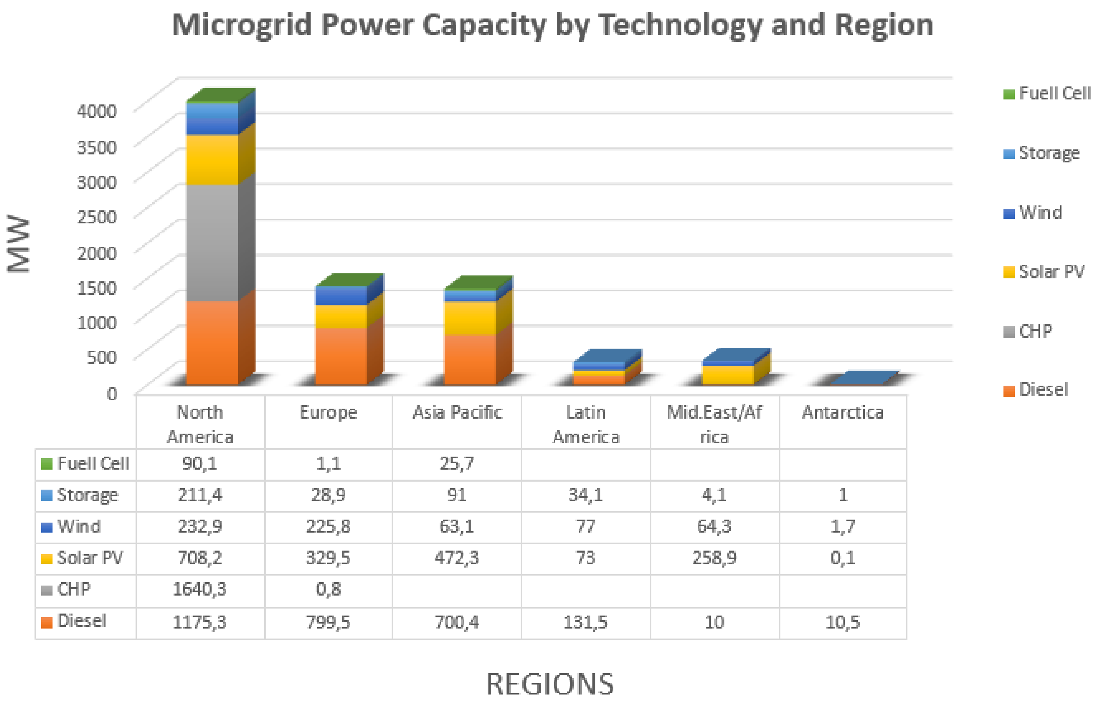
The second country in the Rank by Installed Capacity is China. China is currently revolutioning the energy market and is the country installing the largest amount of renewable energy facilities nowadays.[15] However due to the huge dimension and population of China, with the required infastructure and industry to meet the necessities of this massive country , China is still one of the most polluting ones. Taking a look at the right side of figure6, eventhough China has the second largest installed capacity, with 4267,9 MW only has 31 projects, what means that big microgrids systems are being developed. Number 1 and 2 are clearly predominant, however there is like a step of nearly 3000 MW of difference till we find the other countries in the following order: Russia, Canada, Australia, Indonesia, India, Denmark, France, Haiti and Others. As general features we can distinguish that in Europe, Denmark and France are the leading countries by installed capacity while Spain and France have the largest number of projects.

### Analysis 2: Microgrid Power Capacity by Technology and Region

To perform this analysis, the world is divided in 6 regions: North America, Latin America, Europe, Middle East/Africa, Asia Pacific and Antarctica. The Technologies studied are Diesel, Combined heat and power (CHP), Solar Photovoltaic, Wind, Storage Systems, Fuel Cells and Other. Figure 7 contains the data evaluated in this analysis from Navigant Report World Markets 2016. In order to provide a more illustrative view, Figure 8 is created with Excel. In this graphical representation, Megawatts are plotted versus Regions. In this cumulative graph, it can be seen that North America is by far, the region with the largest microgrid power capacity, where the predominant technologies are CHP and Diesel.
Europe and Asia Pacific are almost on the same level, but in this case the predominant technologies are Diesel and Solar PV energies. Although the largest contributant in North America was CHP, in Europe it is almost insignificant and not even present in the other regions.
Latin America's microgrids are powered with Diesel, Wind, Solar PV and storage while Middle East/Africa region is mainly supported by solar PV, followed by Wind and a small contribution form Diesel and storage.
The last region analysed is Antarctica, with almost negligible values compared to the other regions.

| TOTAL MICROGRID POWER CAPACITY BY TECHNOLOGY AND REGION, WORLD MARKETS 2016 (MW) | | | | | | | |
|---|---|---|---|---|---|---|---|
| Region | Diesel | CHP | Solar PV | Wind | Storage | Fuel Cell | Other |
| North America | 1175,3 | 1640,3 | 708,2 | 232,9 | 211,4 | 90,1 | 629,2 |
| Europe | 799,5 | 0,8 | 329,5 | 225,8 | 28,9 | 1,1 | 137,6 |
| Asia Pacific | 700,4 | _ | 472,3 | 63,1 | 91 | 25,7 | 211,8 |
| Latin America | 131,5 | _ | 73 | 77 | 34,1 | _ | 4,2 |
| Mid.East/Africa | 10 | _ | 258,9 | 64,3 | 4,1 | _ | 22,6 |
| Antarctica | 10,5 | _ | 0,1 | 1,7 | 1 | _ | _ |
| TOTAL | 2827,3 | 1641 | 1842 | 664,8 | 370,5 | 116,8 | 1005,4 |

**Figure** 7: Total Microgrid Power Capacity by Technology and Region, World Markets 2016 [5]




| | North America | Europe | Asia Pacific | Latin America | Mid.East/Africa | Antarctica |
|---|---|---|---|---|---|---|
| Fuell Cell | 90,1 | 1,1 | 25,7 | | | |
| Storage | 211,4 | 28,9 | 91 | 34,1 | 4,1 | 1 |
| Wind | 232,9 | 225,8 | 63,1 | 77 | 64,3 | 1,7 |
| Solar PV | 708,2 | 329,5 | 472,3 | 73 | 258,9 | 0,1 |
| CHP | 1640,3 | 0,8 | | | | |
| Diesel | 1175,3 | 799,5 | 700,4 | 131,5 | 10 | 10,5 |

**Figure** 8: Graph of Microgrid Power Capacity by Technology and Region

## 2.4. Challenges of the Islands

Islands all around the world, despite their diversity of energetic systems and policy frameworks, face common challenges regarding the quality, reliability and affordability of electricity. Islands are also a key part in this power transition the world is going through. According to EUROSTAT definition, " islands are considered all those territories with a minimum surface of 1 km square, a minimum distance of 1km to the mainland with no fixed link and a resident population of more than 50 inhabitants". [23]
Many islands face electricity problems due to lack of infrastructure, lack of investments on energy and low incomes, resulting on fragile economies. Moreover it has to be taken into account that many islands are considered UNESCO World Heritage Sites, therefore the challenge lays in how to provide secure, clean and reliable electricity in a sustainable way without damage the environment. Acknowledging the special needs of islands is essential to provide the required solutions.
As mentioned in EURELECTRIC report [27] due to the isolated nature of islands, they are suitable scenarios to install, implement and test innovative technologies and microgrids. Islands as well as mainlands, used to rely on fossil fuel production methods, being strongly affected by global prices fluctuations. Besides, fossil fuel import prices in islands are considerably higher than in mainlands, due to shipping cost and lack of large fuel storage facilities. In terms of power production, as islands can not be benefited from economies of scale, electricity final price is even higher. All the dissadvantages presented, among many others, gave rise to renewable energy systems and microgrid projects. Swifting away from fossil fuels to renewable energy sources is helping island's economines. With an initial investemt

in the required technology and taking advantage of the natural resources given in the area, clean and more affordable energy can be supplied to the islanders. Natural resources may change from an specific area to another, however the most common ones are solar energy and wind energy. Due to the intermittency of these resources, storage systems were implemented to store the excess of energy for a later use when environmental conditions are not suitable for energy production. As a further step, remote microgrids projects were introduced, creating a small version of the grid with distributed generation, storage systems and different loads spread in the specific area. Microgrids introduction is a huge improvement cause allows the do demand side management (modify the demand to better match the generation) and peak shaving providing better energy for the community. As the Irish proverb says: "*There is no Strength without Unity*"

Among all the islands with hybrid systems, as mentioned in section 1, the chosen one for this study is Isabela Island, in Galapagos.

# 3. Overview of the Galapagos Archipelago: Energetic framework and transition

Ecuador is a contry located in the North-west part of the South American Continent, at the ecuator's latitud. Around 1.000 kilometers away from the Ecuadorian coast, in the Pacific Ocean, the Galapagos Archipelago is located. Galápagos Archipelago is composed of 13 big islands, 6 islands of medium size, more than 40 small ones and a unique surrounding marine reserve of 140.000 Km squared [9]. Situated in a high seismic and volcanic area where three different marine currents come together, unusual landscape and animal life emerged thousands of years ago, receiving the actual name of " *living museum and showcase of evolution*". [28] Figure 9.


**Figure** 9: Galapagos Archipelago [6]

These islands were discovered unnintentionally in 1535 by Bishop Tomas Berlanga, who drifted off course in his journey between Panama and Peru. For more than 300 years, the Archipelago was used mainly by buccaneers, sealers and whalers, to anchor the boats, take provisions and rest. [29] It was not until year 1832 that Galapagos was officially claimed by Ecuador, however for the following decades foreigner countries tried to collonized them intermittently. The Galapagos' most famous visitor was Charles Darwin in 1835, who spent almost five weeks in the islands taking notes of the ecosystem, that later would be really relevant for his *theory of evolution*. In 1959, 97 % of the Archipelago became officially Natural Park and later it got other titles such as Marine Reserve, UNESCO World Heritage and Biosphere Reserve.[28]
Since that moment, population in the islands started to increase rapidly, as it can be seen in figure 10, before year 2010 resident population accounted already for nearly 20.000 people and the number of tourist overpassed the 140.000 people. According to [30] the population growth, mostly driven by tourism, resulted in an infrastructure increasement that started to endanger the ecosystem and due to this reason, measurements to control inmigration and tourism were implemented.

[7]

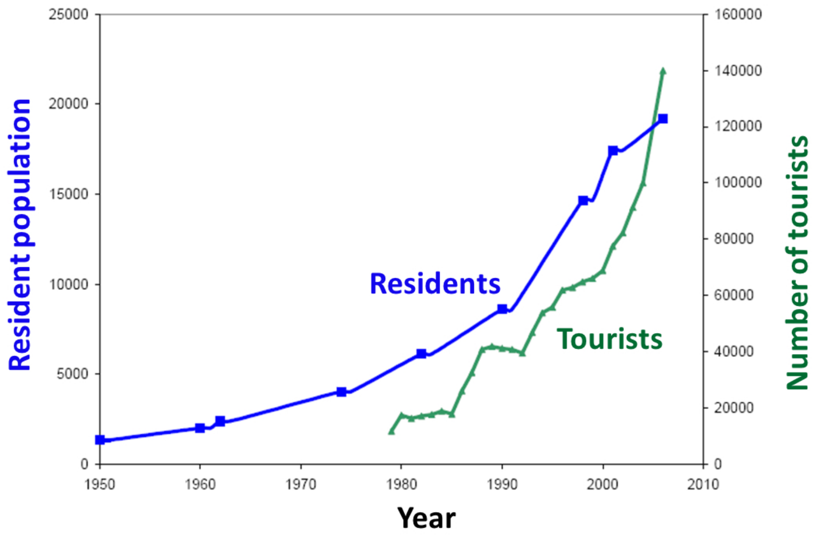



**Figure** 10: Population and Tourism growth in Galapagos Archipelago 1950-2010[7]

Among all the islands that make up the Archipelago, only four of them are inhabitated. The names of these islands are Santa Cruz, San Cristobal, Isabela and Floreana, being Puerto Baquerizo Moreno in San Cristobal island, the capital of the archipelago. Nowadays the most populated island is Santa Cruz, followed by San Cristobal, Isabela and the less populated one is Floreana.

## 3.1. Energetic framework of the Archipelago

Over the years, as the population and infrastructure increased, the energy demanded increased as well. From 1999 to 2016, there was an average annual growth rate of 9 % in energy demanded [10], where the largest consuming sectors were transportation, residential and comertial sectors. Figure 11 represents the share of energy consumption of the main islands. Santa Cruz, as it is the most populated island, has the largest share of energy consumption in Galapagos, with a 60 % of total energy. San Cristobal island, although is the capital, only accounts for 30 % of total demand, while Isabela accounts for 9 % and Floreana barely reaches the 1 % of final consumption. The graph is created with real data measured in the location from year 2012 to year 2015, provided by ELECGALAPAGOS, the electric company of The Galapagos Islands.

According to historical available data, the largest component in the generation mix of the Archipelago was Thermal energy, obtained by burning fossil fuels. For years the Archipelago used fossil fuels to meet the energy requirements of the inhabitants, polluting and damaging the islands. In fact, there have been many ocassions where both the environment and people have suffered from petrol poured accidentally in the ocean. The worst dissaster Galápagos went through, occured in January,17 year 2001, when the tanker Jessica leaked about 570.000 Liters of

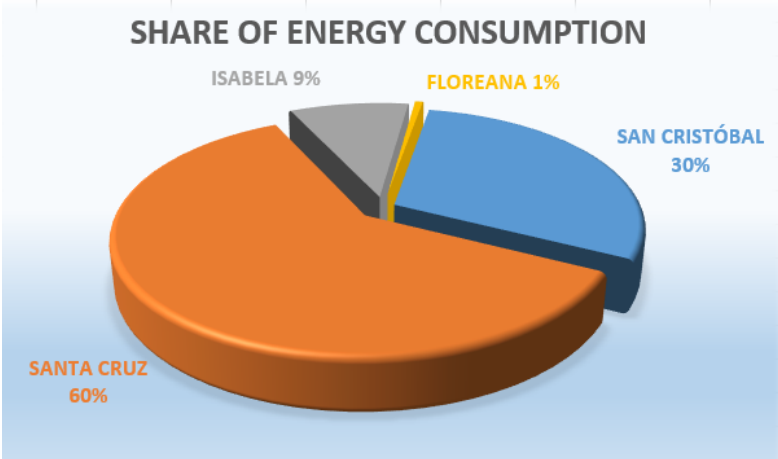



**Figure** 11: Share of energy consumption in the inhabitated Islands of Galapagos

diesel to the ocean that had devastating effects in the Archipelago's ecosystem and species [31]. In order to mitigate the effects of fossil fuels, the Government stablished the ' *Iniciativa Nacional Cero Combustibles Fósiles para Galápagos*' in 2008, that is a national policy against fossil fuels in the Galapagos Islands, especially in the electricity and transportation sectors. That was the beginning of the transition towards a sustainable future. Renewable energy was implemented for the first time in 2007, when the first wind farm began to operate in San Cristobal island and afterwards multiple projects of renewable energies had been accomplished. Nowadays, solar energy, wind energy and biodiesel (pine oil or jatropha oil) are transforming the generation mix.[10] Table 1 shows the installed capacity of the archipelago in 2016.

| Island | Thermal | Wind | Solar PV | Batteries |
|---|---|---|---|---|
| San Cristóbal | 9.450kW | 2.400kW | 12,5kW | |
| Santa Cruz | 14.950kW | 2.250 kW | 1.567kW | Pb-Acid:500kW; 4.032kWh<br>Li-ion:500kW; 268kWh |
| Isabela | 2.640kW | | | |
| Floreana | 283kW | | 20,9kW | Pb-Acid:36kW; 96kWh |

**Table** 1: Installed nominal power in the four inhabitated islands of Galapagos [10]

## 3.2. Isabela Island

### 3.2.1. Introduction

Isabela is the biggest island in The Galapagos Archipelago, with a surface of 4588 km squared, represents almost the 60 % of the total land surface. Isabela is also the youngest island of Galápagos, with less than 1 million years. The name of Isabela comes from the spanish Queen Isabel of Castilla, who supported financially the trip of Cristóbal Colón. The unusual shape of the island, like a sea horse, comes from the merger of 6 big volcanos in a unique surface.[9] Figure 12 is a satellite view of Isabela Island from google maps.


**Figure** 12: Isabela Island Satellite View

The economy of the island is based on fishing, farming and tourism, where the center of population is found at the south area in Puerto Villamil. In this area is located the Thermal power plant that generates electricity for the whole island, where ELECGALAPAGOS is the electrical company on charge of electrification and power generation. Isabela has a 100 % thermal electric background, where all the electricity came from burning fossil fuels in diesel generators.[10] Real generation values in kWh from 2012 to 2015, provided by ELECGALAPAGOS, are plotted in figure 13 , where vertical lineas are drawn on purpose to easily distinguish the different years. Analysing the graph, it can be seen that there is a seasonality in the generation, where peak season takes place on march and low season around september. Besides, another feature that can be notticed is that generation has been growing gradually over time, reaching a value of approximately 480.000 kWh at the end of 2015. Table 2 shows the different generators working on Isabela and their characteristics. Generators number 1, 2 and 4 are from the CATERPILLAR brand and the number 6 is from KOLHER-MTU brand, the four of them powered with diesel. The total amount of nominal power accounts for 2.640 kW, however as the peak demand never reaches that value, the generators work alternately to meet the demand. [10]

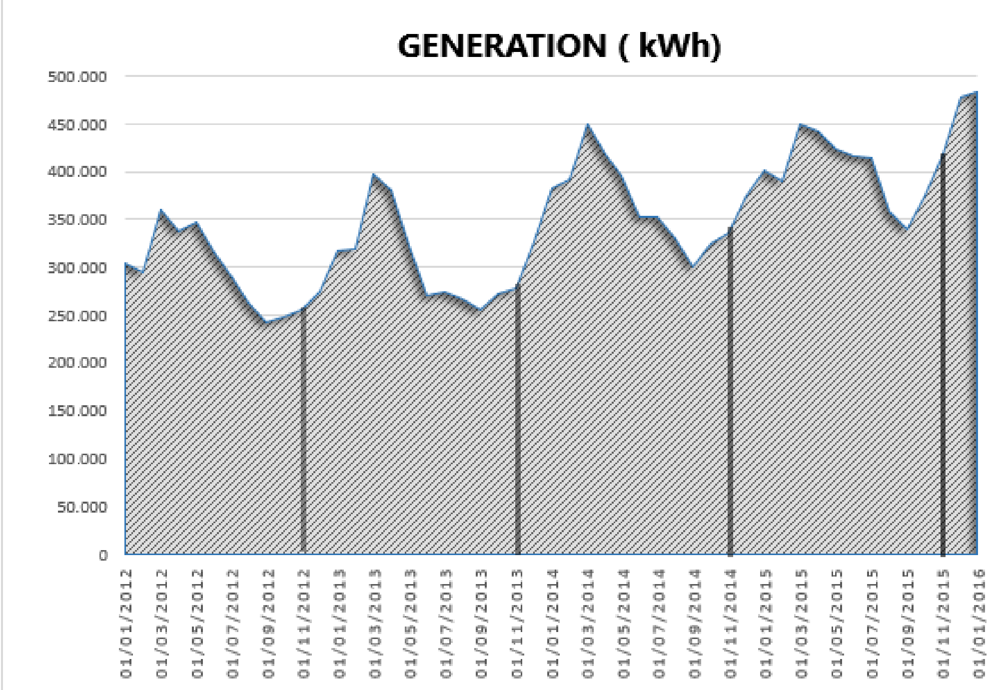



**Figure** 13: Isabela Island Power Generation in kWh (2012-2015)

| Number | Producer | Model | Year | Nominal Power(kW) |
|---|---|---|---|---|
| 1 | CATERPILLAR | 3512 | 1990 | 650 |
| 2 | CATERPILLAR | C18 | 2010 | 545 |
| 4 | CATERPILLAR | C18 | 2010 | 545 |
| 6 | MTU | 1.6VG85 | 2013 | 900 |
| | | | **Total Isabela** | **2640 kW** |

**Table** 2: Installed nominal thermal power in Isabela [10]

### 3.2.2. Hybrid System analysis

As mentioned earlier, Galapagos is implementing policies to accelerate the transition towards a sustanaible energy system. Few years ago, some projects began to be implemented to set aside fossil fuels and begin to take advantage of renewable energies. The first project got deployed in 2007 in San Cristóbal island, where the first wind farm " El Tropezón" started to operate. In the years that followed, renewable energy projects were implemented as well in Santa Cruz and Floreana, nevertheless, Isabela remained generating energy exclusively from fossil fuels. According to [10], due to the renewable energy projects, by year 2015 there had already been savings of 2,9 millions of gallons of diesel, avoiding the emission of approximately 27.934 tones of carbon dioxide to the atmosphere. In 2011 a "Hybrid System in Isabela Island" was designed, reviewed in 2012 and set to start the operation by the end of 2017. All the information and development of this project can be found in [9].

A hybrid system is a system that combines two or more different energies with storage units to produce electricity. They can be powered only with renewable sources or with both renewable and non-renewable sources, that combined with storage systems allow the reduction of fuel consumption by taking advantage of renewable resources. Figure **??** is an example of a hybrid system which components are: wind turbine, PV modules, generators, battery bank and load.

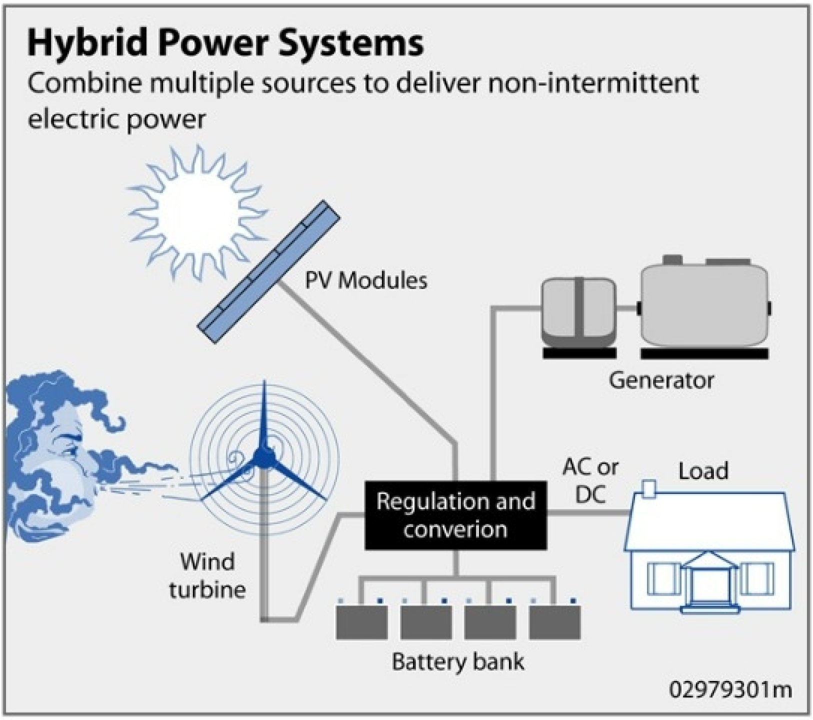



**Figure** 14: Hybrid wind, solar and thermal system scheme [8]

The working principle of a hybrid system composed of solar PV, generators and batteries is shown in figure 15 . First of all, line *red* represents the demand during a one-day period. During sun light hours and if the environmental conditions are suitable, PV pannels are producing enough energy to first meet the demand (color *yellow*), and second, if extra energy is produced, can be stored in storage systems, usually baterries (color *dark green*). When the sun fades or the environmental conditions are not appropiate, generators start to operate (color *blue*). Generators usually produce a certain amount of power, therefore if the demand increases above this level, they can either turn on another generator to add the power or use the energy stored in the batteries. Color *light green* represents the time when batteries are discharging the power previously stored. Batteries usually have two control systems: load following and cycle charging. When the load following (LF) strategy is used, the batteries are charged only with extra renewable energy. However if the cycle charging (CC) strategy is used, batteries can be charged with extra energy produced by the generators as well as with renewable energy. In this case, it can be seen in Figure 15 that cycle charging strategy is being used, however is preferred to charge them with the solar systems since the sun is a free source and generators require the input of fuel.

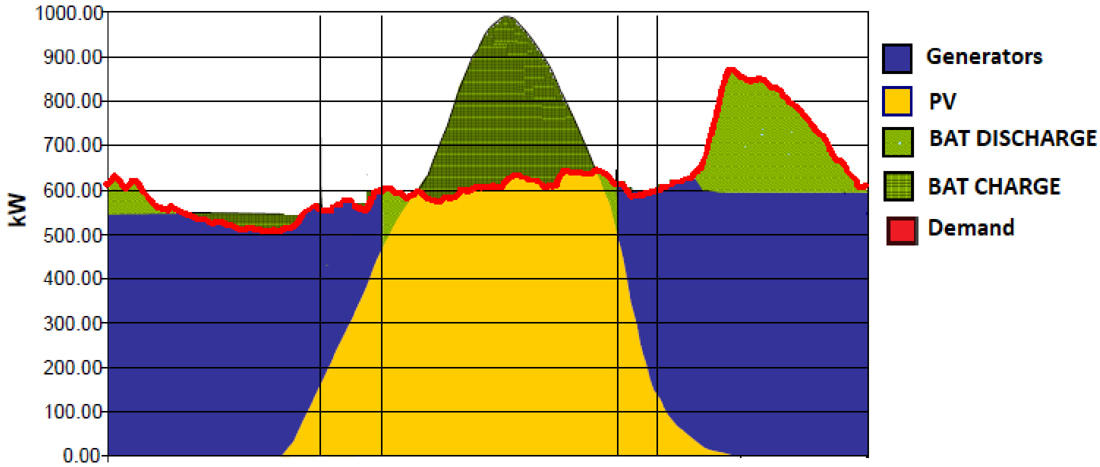



**Figure** 15: Functioning Scheme of a typical solar-thermal hybrid system [9]

The Hybrid system installed in Isabela, table 3, is composed of 1625 kW of thermal energy, 922 kWp of solar photovoltaic energy and a battery bank of 833 kW and 258 kWh. Thermal energy is provided by 5 dual generators of 325 kW each, that can either function with diesel or biodiesel.

| HYBRID SYSTEM | | |
|---|---|---|
| **Thermal** | **Solar PV** | **Batteries** |
| Dual Gen 1: 325 kW | 922 kWp | Li-ion: 833kW; 258 kWh |
| Dual Gen 2: 325 kW | | |
| Dual Gen 3: 325 kW | | |
| Dual Gen 4: 325 kW | | |
| Dual Gen 5: 325 kW | | |
| Total Thermal: 1625 kW | | |

**Table** 3: Hybrid System installed capacity in Isabela Island [10]

The Hybrid project is located at the same spot than the previous thermal power plant, at 800 m from Santiago Villamil. Figure 16 shows the scheme of the new system, where the solar photovoltaic part (right side) and the thermal part (left side ) are found right next to each other. Old installations are reconditioned and used to enclusure the generators of the new thermal power plant. [9]

According to [9] in order to assure a good functioning of the hybrid system designed by ELECGALAPAGOS, there are requirements some that need to be fulfilled.

#### Minimum Requirements for the Hybrid System

**Figure** 16: Implementation plan of Isabela's Hybrid System view [9]

As said in [9], these are the minimum requirements of Isabela's hybrid system should accomplished to operate:

1. Off diesel operation mode: The system should be able to operate independently of the thermal power plant whenever the state of charge of the batteries and the solar radition allow it.

2. Diesel and batteries operation mode: Whenever there are adverse environmental conditions, the system should completely satisfy Isabela's full demand with the generators.

3. Uninterrumpible service: The transition between the different operation modes in the hybrid system should be performed without interrumpting the supply.

4. Compensation of the system's fluctuations: The fluctuations produced by the photovoltaic energy or by a suddenly load change should be absorbed by the system itself.

5. Redundancy and parallel operation of the battery bank: Redundancy is mandatory in the level n-1, that means that if ever there is a failure in a bank, the system should still present normal operation. To allow this scenario, battery banks have to be connected in parallel to each other and thus sharing the load.

# 4. Software and simulation models

## 4.1. Software: HOMER Pro

The main Software used to develope the simulations for this Bachelor's Thesis is HOMER Pro. HOMER, which acronym stands for Hybrid Optimization Model for Multiple Energy Resources, is an optimization software for distributed power systems, developed at the National Renewable Energy Laboratory (NREL) in the United States. It was a free software until year 2014, when Homer Energy bought the rights and became a private software called HOMER Pro. HOMER Pro is a really useful software to test microgrid systems in specific locations and study the viability of a project. HOMER's working principle is based on three pillars: [32]

1. **Simulation**: First of all, a scheme of the system has to be built in the program stating the location and inputs of the project. As inputs, the demand for one year period has to be introduced as well as the components of the microgrid, providing the largest amount of data possible to make it more accurate. The components can be power sources such as solar PV pannels, wind turbines, thermal generators, hydroelectric, biomass,etc; and storage systems such as flywheels, batteries, hydrogen,etc. Besides it can even be selected whether the operation mode is connected or isolated form the main grid. Moreover HOMER Pro allows to either introduce data of natural resources in the location manually, such as solar irradition or wind speed, or use a database integrated in the program. Once all those parameters are set, the simulation can be started. For every 8760 hours of the year, Homer makes energy balances comparing the electrical and thermal demand with the energy provided by the system.

2. **Optimization**: Once the simulation is run, homer displays all the possible configurations for the project sorted by the Net present value (NPV) of the project. In those configurations all the relevant data is showed, such as the energy produced by each component, the cost of energy, the period of charging/discharging of the batteries, etc. HOMER shows the results in tables and graphs as well, to allow the comparison among different configurations. As a main feature of the program, Homer detects the inconsistencies of the designs and suggests improvements.

3. **Sensitivity analysis**: Homer has an extra option called sensitivity analysis that allows to identify which factors have the greatest impact on the project. Some variables can be considered sensible inputs and thus Homer repeats the optimization process for each of them. Some examples of sensitive variables are the fuel cost and wind speed. For each different value of the variables introduced, HOMER outputs show how the project would be affected by their change.

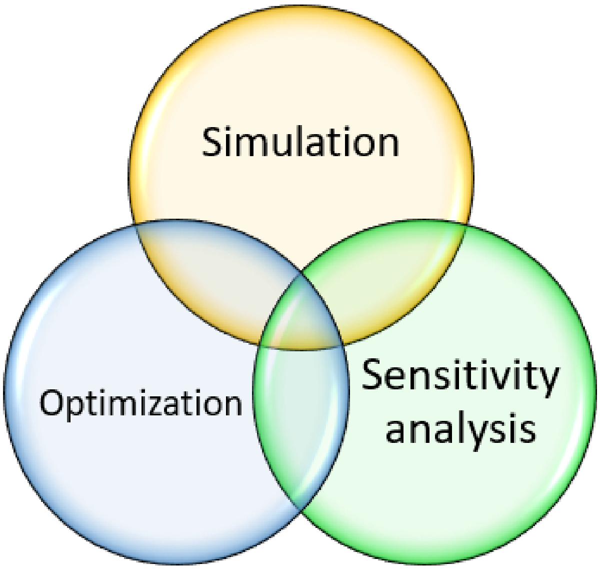



**Figure** 17: Three pillars of Homer

## 4.2. Simulation models

The electric background of Isabela is stated in previous section [3.2]. As mentioned earlier, Isabela Island has been a 100 % Thermal Island with the configuration shown in table 2 . However Isabela, as well as the whole archipelago, is undergoing a transition towards a renewable energy future. It was expected that by the end of 2017 the project 'Hybrid System in Isabela Island' was functioning already, but according to recent information from ELECGALAPAGOS, the project is not working yet.
The goal of this bachelor's thesis is the planification of the electric grid in Isabela up to year 2035, therefore a projection of the demand is going to be performed up to that year and five case scenarios are going to be simulated and analysed with HOMER Pro. The differente models will be studied in years 0, 5, 10 and 20 to see the evolution in time of the system, starting in year 2015 and finishing in year 2035. A brief introduction to each case scenario is explained below:

1. Case 1. The first case that is going to be analysed is the evolution in time of the current 100 % thermal system. In this scenario, Isabela is not implementing any renewable energy technology and therefore is powered only by Diesel generators. In this case the results will show how the thermal system is going to be affected and modified over the time, and the additional capacity that needs to be installed to meet the demand. Besides this case scenario is going to be used to validate the model. Hourly data for the demand and generation values are known for year 2015, therefore introducing the demand and the generators with the specifications given will allow us to verify if the results of the simulation matches reality and the model is valid for the following years. The following simulations are going to be calculated for year 2015, 2020,2025 and 2035.

2. Case 2. The second scenario that is going to be analysed is based on the ' Hybrid System' designed by ELECGALAPAGOS. The information of thermal, solar PV and batteries in table 3 will be used for this simulation. With the demand projection previously calculated, the evolution of this system over time is going to be evaluated keeping the same percentage of renewable energy integration over time. Although real information is used to buil the model, it is not possible to validate as it is not operating yet. Eventhough the system is not operating yet, for this study the first year of simulation is going to be 2015 and up to 2035, always keeping a constant percentage of renewable energy penetration.

3. Case 3. For the third scenario, a Hybrid system similar to the one in scenario 2 is used but capacity installed is modified to provide a 50 % of renewable energy penetration and the modification of the system is analysed from 2015 to 2035. This time Homer is the one sizing the components to meet the requirements.

4. Case 4. The forth scenario is similar to the previous ones but with a renewable energy penetration of 75 %. Homer decides the optimized model and sizes the capacity of the different components, increasing solar energy and batteries while decreasing fossil fuel.

5. Case 5. The last case scenario is a system with a high percentage of renewable energy penetration, mainly powered with solar Pv pannels. The difference between having a system with a 95 % and a system with 100 % renewable energy penetration will be discussed.

## 4.3. Projection of the demand

As the horizont of the study is 2035, a projection of the demand should be estimated. Real demand values of Isabela are provided by ELECGALAPAGOS from 2012 to 2015, that allows to see the trend and seasonality of the demand, shown in figure 18.
To perform the simulations and build a synthetic load profile for every year the simulation wants to be done for, Homer needs 8.760 values, that corresponds to a value per every hour of the year. To calculate the demand that later will be introduced in Homer, the variability of the hourly values of one year are replicated and scaled throughout the years following the seasonality pattern by means of a regression line. Values calculated from 2016 to 2035 are plotted and shown in figure 19. It can be noticed the increasing trend and seasonality previously mentioned of the values, where peak month is march and peak-off is september.

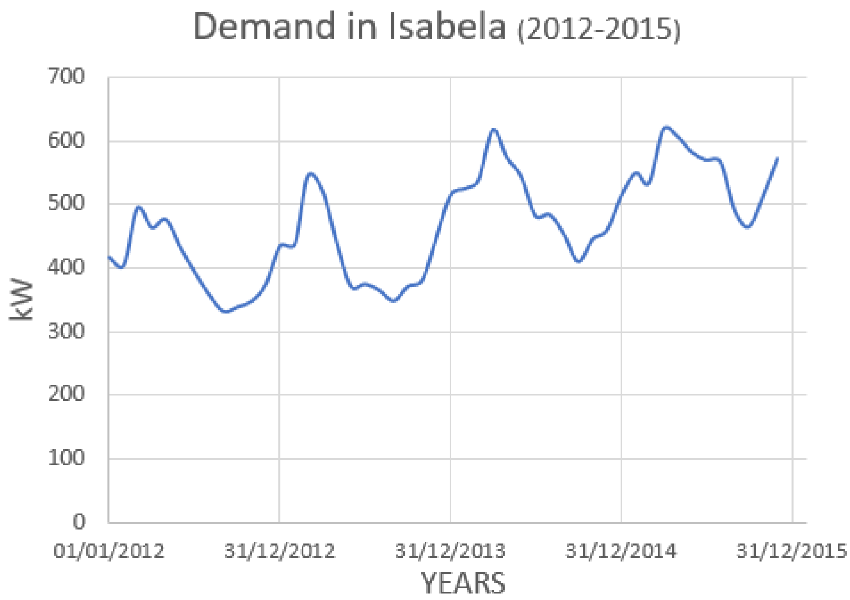



**Figure** 18: Isabela's Real Demand values from 2012-2015

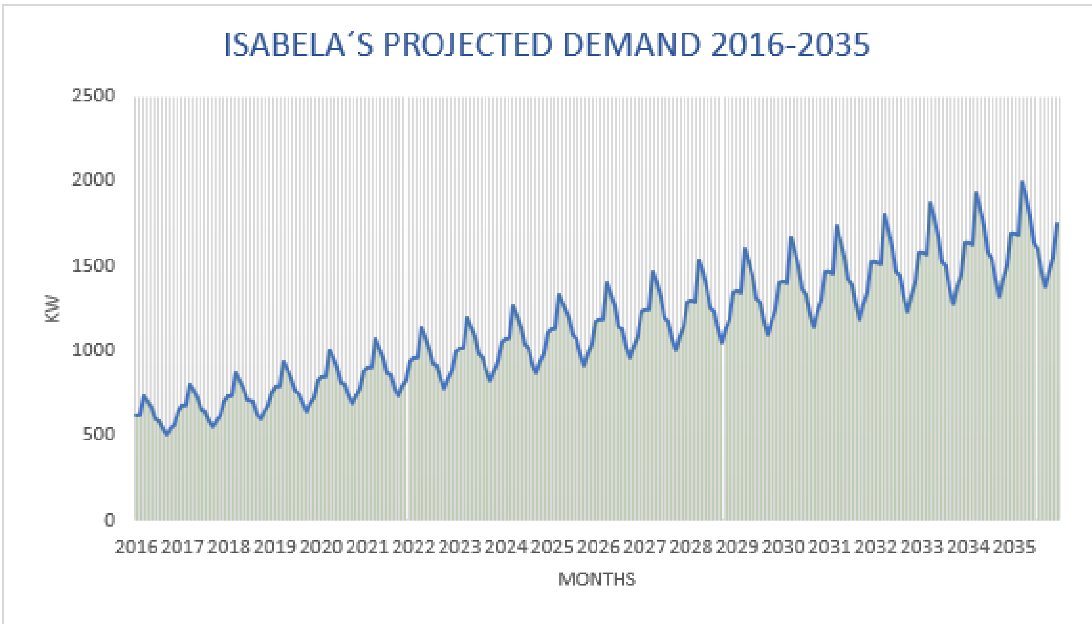



**Figure** 19: Isabela's Calculated Demand Projection 2016-2035

# 5. Case Scenarios

## 5.1. Scenario 1: 100 % Thermal system

### 5.1.1. Simulations

The first scenario analysed is the 100 % thermal system case. As mentioned in previous sections, the electrical background of Isabela Island is a system completely powered with thermal energy obtained by burning diesel in generators. Although

it is known that there is a Hybrid project in Isabela whose operation is expected to begin in 2018, this scenario covers the possibility in which neither that Hybrid system nor any renewable energy source are installed and therefore Isabela keeps producing energy from fossil fuels.
The following simulation is based on information obtained from sources [9] and [10], where the specifications, models and nominal powers of the generators are shown in table 2. Simulations will be performed from 2015 to 2035.

### *Year 2015*

Back in year 2015 this model was working, therefore real data for demand and power generation are known. The main point of simulating the scenario in year 2015 is to validate the model and check if those generators, with the specifications and power given, can meet the demand and the values obtained in the simulation match real historical values. As this is the first simulation performed, the construction of the model is going to be explained step by step.
Steps to construct the model:

**1. Project creation and location search:** Figure 20 shows the main window of HOMER Pro program to define all the parameters that make up the system. The location chosen for this project corresponds to the one shown in Figure 21 . The geographical coordinates are 01°47' 05,57"S and 90°53' 33,50"W.

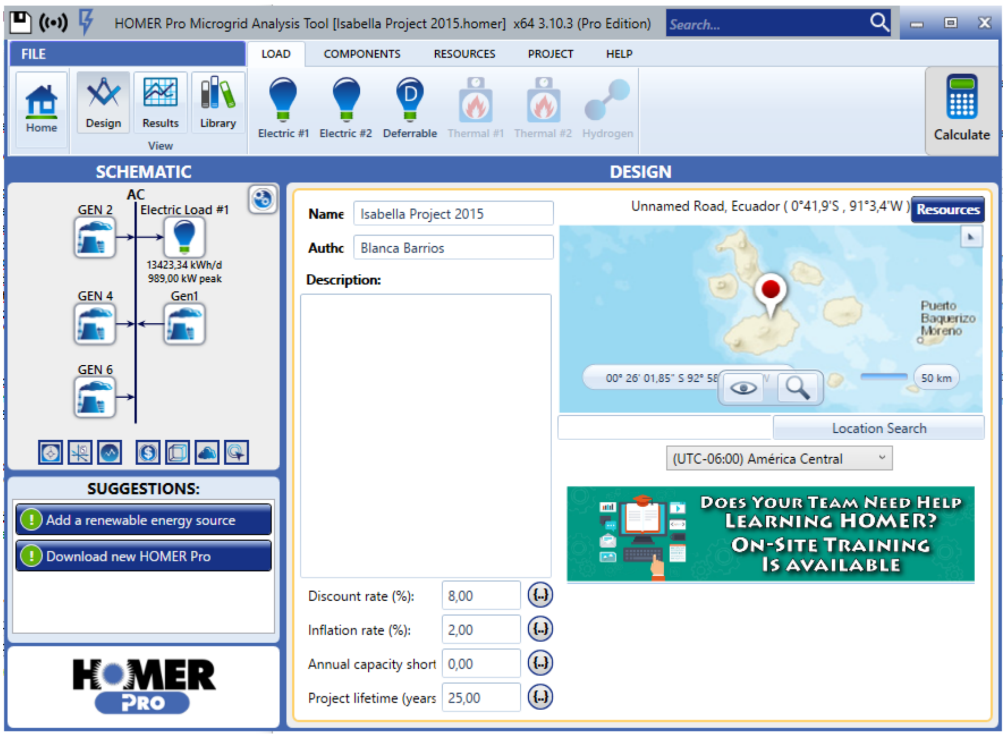



**Figure** 20: Homer's main components setting window


**Figure** 21: Geographical coordinates of Isabela

**2. Introduce the demand:** Homer allows several ways of introducing the demand:

1. Create a synthetic load from a profile: Homer allows to build a synthetic demand by selecting whether there is a peak month or not, and a specific profile between residential, commercial, industrial, community or blank.

2. The second option is to import a file with time series data in hourly values for a one year period. This is the most accurate method.

3. The last option is to use Homer's database to search for a typical profile in a nearby area. However this last option is only available for U.S locations.

The method used in this case is the second one. A file with txt extension is used to introduce the hourly data for a one-year period. As stated earlier, real values provided by ELECGALAPAGOS for year 2015 are used in this simulation. Figure 22 created by Homer represents the seasonal profile with average data in kW versus the different months. It can be seen that for year 2015 the peak month is December, however as mentioned earlier it is known from historical values that this year's profile is unusual. Commonly peak month is march instead of december. Besides, Homer generates a typical day for each month, where kW are plotted versus hours, shown in Figure 23. From these graphs it can be seen that the demand follows approximately a community profile, where peak takes place at night time between 18:00 h and 22:00h.

### 3. Components and specifications

The next step to be accomplished is the selection of the components 2 . Homer has an internal database with generators of different models and capacity whose specifications are known. The model of generator 2 and generator 4 is Caterpillar

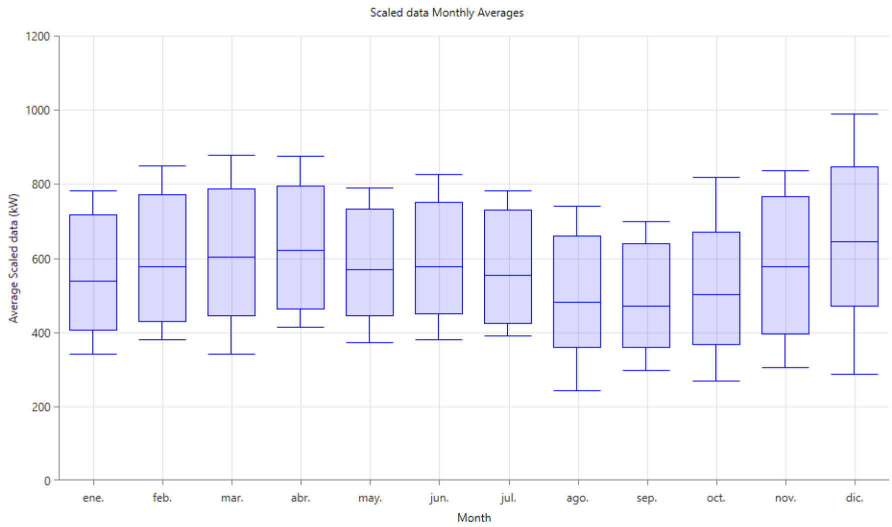



**Figure** 22: Isabela's monthly average data (kWh vs months) 2015


**Figure** 23: Isabela's daily profile (kW vs hours) 2015

C18, that is found in Homer's database, where the specifications are given. However, generator 1 model CAT 3512 and generator 6 model MTU are not registered, thus a typical scalable generator is used and the power is adjusted. As not enough information is known, other default values provided by Homer are left. The total diesel installed capacity in Isabela accounts for 2.046 kW, but the highest peak recorded is only 989kW. It is known that the four generators work intermittently to meet the demand. In a document provided by ELECGALAPAGOS, it is shown the working schedules of each generator during 2015. Figure 25 shows the months in which the generators were working: Generator 1 is working every month, generator 2 from January to June, generator 4 from June to December and generator 6 every month but on May. Homer has an option that allows to introduce the working schedules of each generator during the whole year, selecting Forced on, Forced off and Optimized mode. In the optimized mode, that is the default setting, Homer decides which generators are producing power and which ones are resting. For this simulation the optimized mode is left but for the months that is known that the generators are turned off, and thus in those specific months it is selected the forced off state.

| | GEN 1 | GEN 2 | GEN 4 | GEN 6 |
|---|---|---|---|---|
| January | X | X | | X |
| February | X | X | | X |
| March | X | X | | X |
| April | X | X | | X |
| May | X | X | | |
| June | X | X | X | X |
| July | X | | X | X |
| Augost | X | | X | X |
| September | X | | X | X |
| October | X | | X | X |
| November | X | | X | X |
| December | X | | X | X |

**Figure** 24: Generator's working month schedule [9]

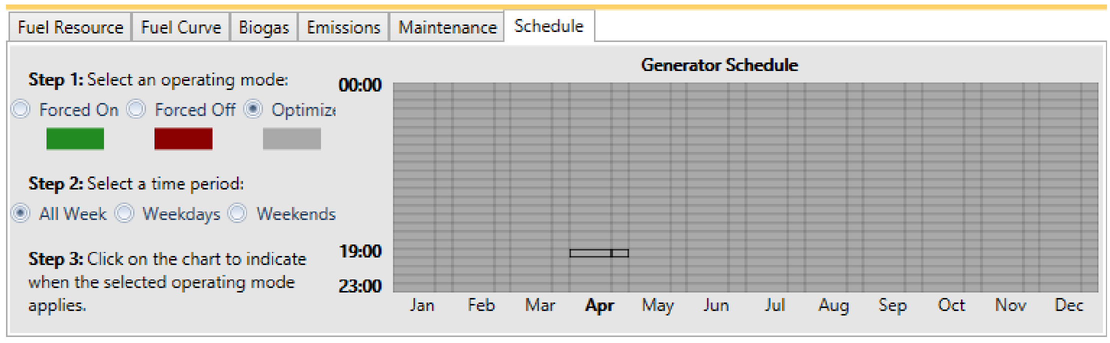



**Figure** 25: Homer's generators schedule setting

In this step it is required to introduce the price of the fuel, that for this study is considered to be 0.8 euros/L. Besides Homer has an option that allows to stablish restrictions to your project. In [9] is said that the system should have an operating reserve just in case there is a failure in a generator or there is an unexpected peak of demand, and should be approximately the 50 % of the capacity of the largest generator. In Isabela the largest generator provides 900 kW, therefore the reserve should be of 450 kW. Considering that the whole systems provides 2.460 kW, the operating reserve accounts for a total percentage of 17 % and this value should be introduced in Homer. Another important thing that is needed to select is the control strategy applied in the system. Homer allows different control strategies, and the main ones are: [32]

1. Cycle Charging: In this strategy, the generator works at maximum power output. When this outoput is higher than the load, the extra energy is used

to other lower priority objectives such as charge the batteries and supply non-priority loads.

2. Load Following: In load following strategy, the generator produces only the exact amount of power to meet the load. Other lower-priority objectives are left to renewable energy output.

3. Generator Order: This dispatch mode follows a priority working order defined in the generator's settings.

For the whole project, the dispatch strategy selected is load following. Once the scheme is finalized, figure 26, simulations are run.

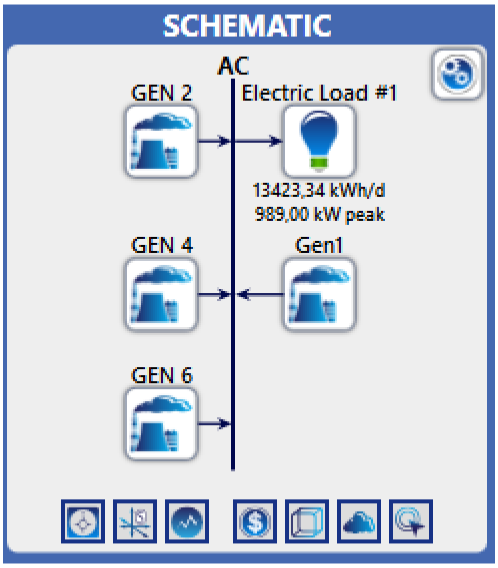



**Figure** 26: Scheme of Isabela's thermal power plant 2015

### 4. Simulations

Homer usually displays different possibilities and suggestions sorted according to the Net Present Cost of the project. According to Homer's manual [32],“ the net present cost of a project (NPC) is the present value of all the cost associated to the project (capital costs, replacement costs, operation and maintenace costs, fuel costs...) during it's whole lifetime minus the present value of the revenues earned over it ”.
Another relevant parameter to analyse the costs is the LCOE “Levelized Cost of Energy”. According to Homer's manual [32] “ the Levelized Cost of energy (LCOE) is the average cost per kWh of useful electrical energy produced by the system ”. The LCOE is a parameter that allows to calculate the present value of all the costs associated to build and operate the system over the lifetime of the project. Homer names this parameter COE, although it stands for LCOE. The results obtained for year 2015 are shown in figure 27 . For the demand, restrictions and specifications introduced, Homer suggests that there are three possible models, sorted

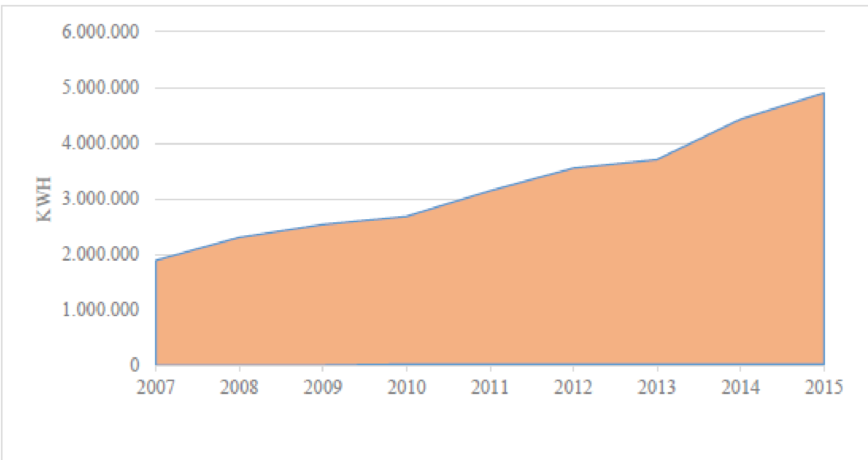
according to the Net Present Cost (NPC) of the project. Homer suggest that a system with less generators can still meet the demand at lower cost, however the solution analysed is the one that corresponds to the current know situation, where all the generators are functioning. Results of working hours, power produced and fuel consumed of each generator are arranged in table 4 for an easier comparison.

| Architecture | | | | | Cost | | | |
|---|---|---|---|---|---|---|---|---|
| GEN 2 (kW) | GEN 4 (kW) | Gen1 (kW) | GEN 6 (kW) | Dispatch | COE (€) | NPC (€) | Operating cost (€) | Initial cap (€) |
| 545 | | 650 | 900 | LF | 0,229 € | 14,5 €M | 1,07 €M | 690.000 € |
| 545 | 545 | 650 | 900 | LF | 0,231 € | 14,7 €M | 1,06 €M | 920.000 € |
| 545 | 545 | 650 | | LF | 0,246 € | 15,6 €M | 1,15 €M | 690.000 € |

**Figure** 27: Simulation results 2015 Scenario 1

| | | RESULTS FOR 2015 | |
|---|---|---|---|
| **Name** | **Working Hours** | **Production (kWh)** | **Fuel (L)** |
| **GEN 1** | 640 | 311.882 | 90.554 |
| **GEN 2** | 672 | 138.854 | 41.601 |
| **GEN 4** | 146 | 25.232 | 7.779 |
| **GEN 6** | 8.005 | 4.423.550 | 1.180.209 |
| | **Total** | 4.899.518 kWh | 1.320.143 L |

**Table** 4: Homer Results 2015 scenario 1




**Producción de energía eléctrica Isabela 2007-2015**
**Fuente: ELECGALAPAGOS. Elaboración: MEER, ELECGALAPAGOS**

**Figure** 28: Real Electric production Values in Isabela 2007-2015 (kWh) [10]

The total production of the system in kWh accounts for 4.899.518 kWh, value that matches the data shown in figure 28 for 2015, where kWh produced are nearly 5.000.000, therefore the model is validated.

Homer decides which generators are functioning in every time step considering the restrictions introduced. As said before, generators work alternatively and this behavior can be seen in figure 29. Line *red* represents the AC primary load (demand) and the other colors represent the different generators working to meet it. Generator 6 (GEN 6) color *gray* can provide 900 kW of power output. However when the demand is above 900 kW, another generator is started to work simultaneously to meet the demand. A feature of generators is that they have a minimum load ratio, which means that when a generator is started it can only work above its minimum load ratio. In this case, Generator 2 (GEN 2) color *green*, has a minimum load ratio of 30 % of its output power, and when it is started it provides approximattely 170 kW. In order to not produce extra energy that is going to be wasted, GEN 6 decreases its power output in such a way that the total amount of power out perfectly matches the demand without wasting energy and fuel. On the left side of the chart, is the same case as explained above but generators 1 ( color *blue*) and 2 are working. As shown in figure 25 on May GEN 6 is turned of and therefore GEN 1 is working, otherwise Homer prefers the GEN 6 to work.

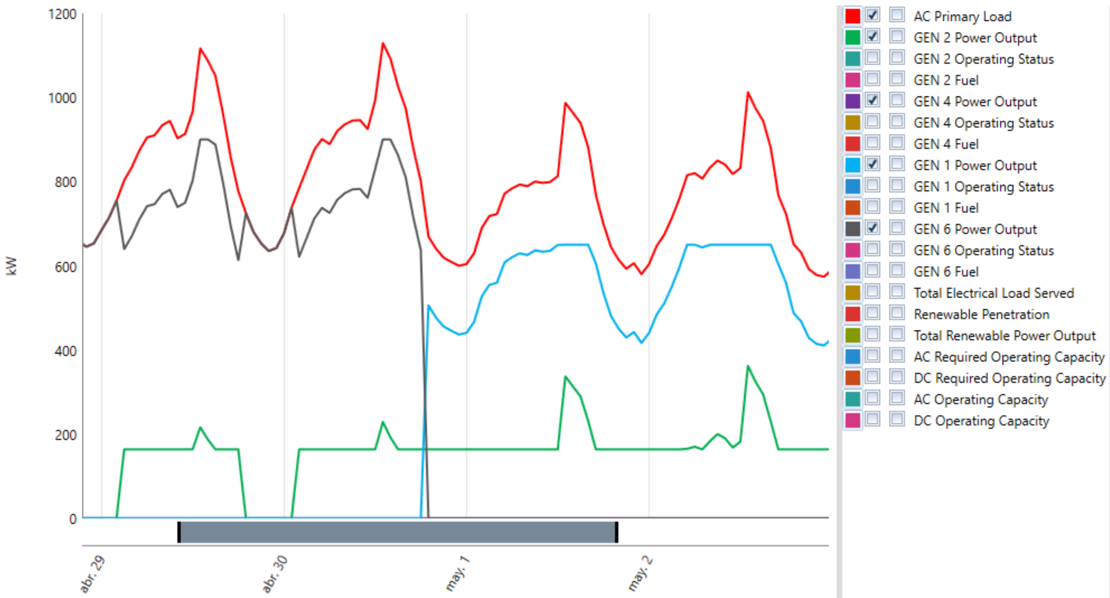



**Figure** 29: Generators output power vs primary load, scenario 1 2015

Figure 30 contains the summary of fuel consumption and emissions of the system during the whole year. The total fuel consumed in 2015 is 1.320.143 L, and average vale of 3.617 liters per day. The huge amount of fuel consumed translates into emissions to the atmosphere, highlighting that almost 3.5 millions of kg of carbon dioxide are released to the atmosphere per year.

| Quantity | Value | Units |
|---|---|---|
| Total fuel consumed | 1.320.143 | L |
| Avg fuel per day | 3.617 | L/day |
| Avg fuel per hour | 151 | L/hour |

| Quantity | Value | Units |
|---|---|---|
| Carbon Dioxide | 3.462.146 | kg/yr |
| Carbon Monoxide | 17.702 | kg/yr |
| Unburned Hydrocarbons | 917 | kg/yr |
| Particulate Matter | 151 | kg/yr |
| Sulfur Dioxide | 8.462 | kg/yr |
| Nitrogen Oxides | 4.463 | kg/yr |

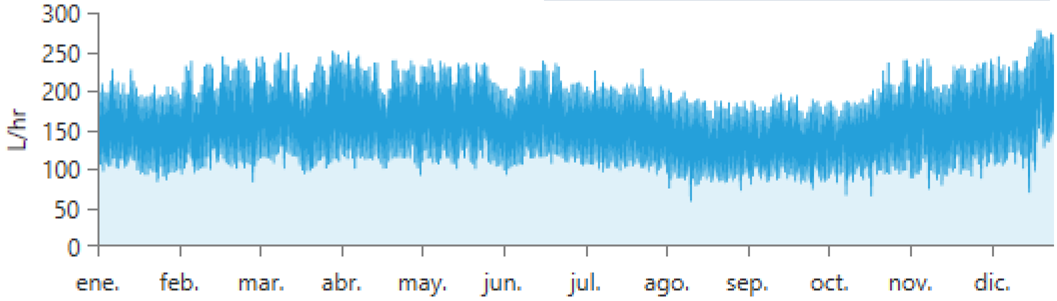



**Figure** 30: Fuel and emissions summary 2015 scenario 1

***Year 2020***

The next simulation performed corresponds to year 2020, where the same system (with same specifications, generators and capacity installed) is used to run 2020 simulation, only demand is modified. Monthly profile and daily profile of the demand are shown in figures 31 and 32 . Demand in year 2020 follows the usual behaviour with peak month in March and peak-off on September. In this year there is a difference compared to 2015.

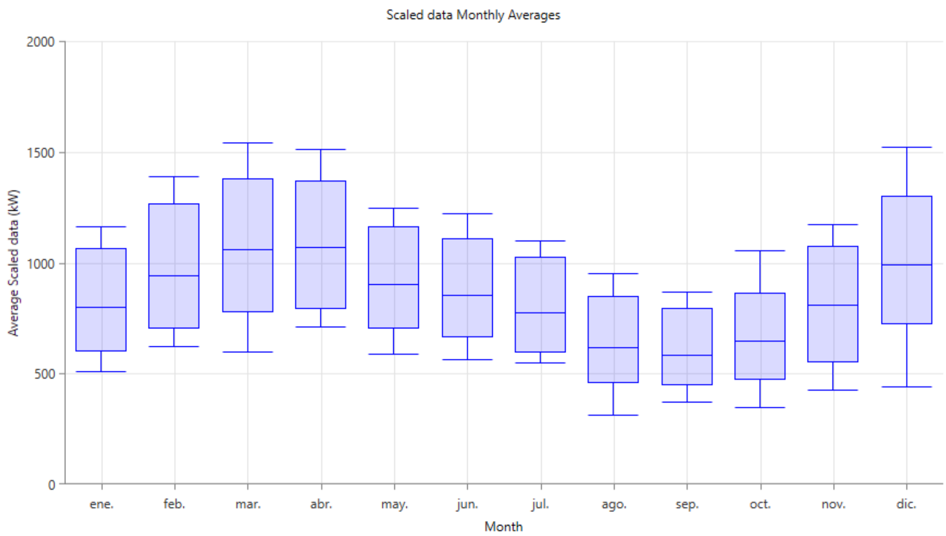



**Figure** 31: Isabela's monthly profile (kWh vs months) 2020

As mentioned in the documents, the generators usually alternate to provide the power required to meet the demand, however in this case, if the alternance of the


**Figure** 32: Isabela's daily profile (kW vs hours) 2020

generators is left as said in 25 , the generation is unsuficient to meet the demand. To perform the simulation, that restriction is removed while the other parameters remain unchanged and the following results are obtained,33. Again Homer suggests different possibilities removing generators, but it is analysed the one with all the generators. Results are arranged in table 5 for an easier comparison. As more energy porduction is required that in 2015, the generators have to working more hour which means more liters of fuel consumed and more emissions.

The monthly average electric production of the system is shown in figure 34. Due to the rised demand, there are some moths (March, April and December) in which all the generators have to be working at the same time to cover all the demand, therefore this image shows why the forced alternance of the generators had to be removed and optimized mode is chosen.

| Architecture | | | | | Cost | | | |
|---|---|---|---|---|---|---|---|---|
| GEN 2 (kW) | GEN 4 (kW) | Gen1 (kW) | GEN 6 (kW) | | COE (€) | NPC (€) | Operating cost (€) | Initial cap (€) |
| 545 | 545 | | 900 | LF | 0,225 € | 21,3 €M | 1,59 €M | 690.000 € |
| 545 | | 650 | 900 | LF | 0,225 € | 21,3 €M | 1,59 €M | 690.000 € |
| | 545 | 650 | 900 | LF | 0,225 € | 21,3 €M | 1,59 €M | 690.000 € |
| 545 | 545 | 650 | 900 | LF | 0,226 € | 21,5 €M | 1,59 €M | 920.000 € |
| 545 | 545 | 650 | | LF | 0,237 € | 22,5 €M | 1,69 €M | 690.000 € |

**Figure** 33: Simulation results 2020 Scenario 1

| | | RESULTS FOR 2020 | |
|---|---|---|---|
| **Name** | **Working Hours** | **Production (kWh)** | **Fuel (L)** |
| **GEN 1** | 251 | 94.026 | 28.357 |
| **GEN 2** | 4.914 | 906.520 | 276.434 |
| **GEN 4** | 156 | 25.506 | 7.941 |
| **GEN 6** | 8.760 | 6.312.913 | 1.650.727 |
| | **Total** | 7.338.965 kWh | 1.963.459 L |

**Table** 5: Homer Results 2020 scenario 1

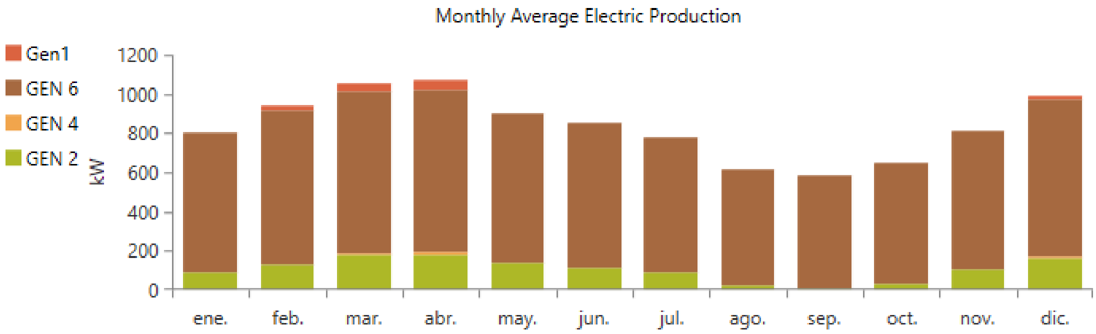



**Figure** 34: Montly average electric production 2020

### ***Year 2025***

Simulation for year 2025 is similar than the one of year 2020. Montlhy profile and daily profile of the demand are shown in figures 35 and 36.The original installed capacity of 2.450 kW is still able to meet the demand of Isabela Island for year 2025, only the energy produced by those generators has to increase. Results of the simulation are shown in figure 37 and table 6.

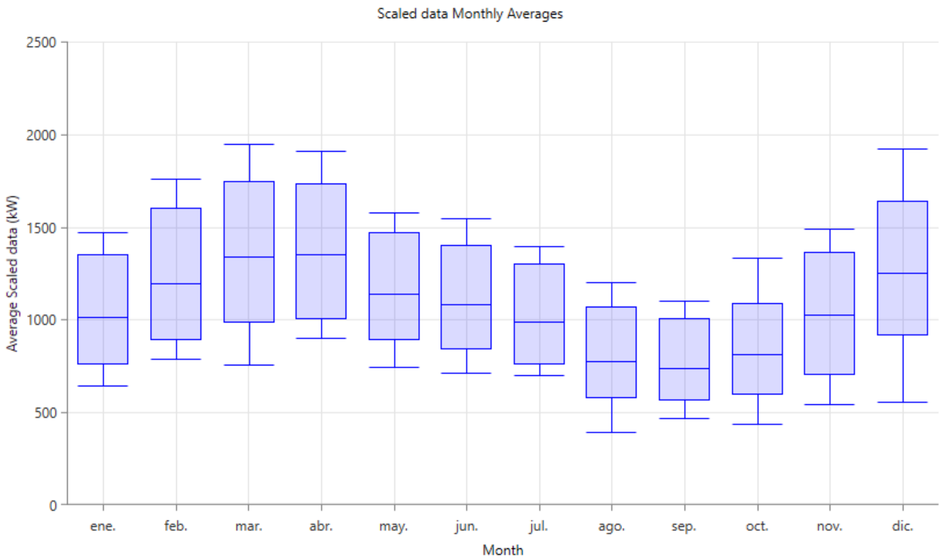



**Figure** 35: Isabela's monthly profile (kWh vs months)2025


**Figure** 36: Isabela's daily profile (kW vs hours) 2025

Although the system still meets the demand and operating reserve, it can be seen in figure 38 that most of the time the four generators have to be operating at the same. In the previous years Homer suggested different options cause with less generators the demand could still be met, however in this year the four generators are required and that is why there is only one option displayed in figure37. This situation is starting to risk the electrical stability and security of supply of Isabela, where if ever one of the generators fails there can be a shortage of supply.

| Architecture | | | | | Cost | | | |
|---|---|---|---|---|---|---|---|---|
| GEN 2 (kW) | GEN 4 (kW) | Gen1 (kW) | GEN 6 (kW) | | COE (€) | NPC (€) | Operating cost (€) | Initial cap (€) |
| 545 | 545 | 650 | 900 | LF | 0,225 € | 28,4 €M | 2,13 €M | 920.000 € |

**Figure** 37: Simulation results 2025 Scenario 1

| | | **RESULTS FOR 2025** | |
|---|---|---|---|
| **Name** | **Working Hours** | **Production (kWh)** | **Fuel (L)** |
| **GEN 1** | 1.015 | 453.160 | 133.123 |
| **GEN 2** | 6.998 | 1.743.137 | 509.033 |
| **GEN 4** | 1.959 | 331.699 | 102.627 |
| **GEN 6** | 8.760 | 7.245.370 | 1.878.246 |
| | **Total** | 9.773.366 kWh | 2.623.029 L |

**Table** 6: Homer Results 2025 scenario 1

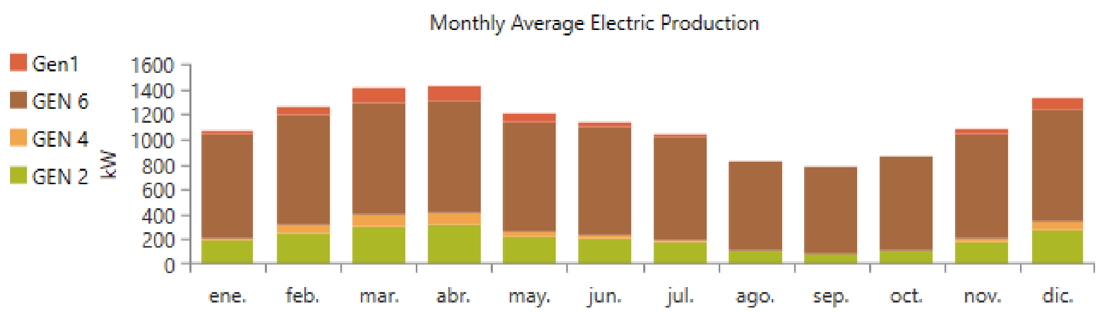



**Figure** 38: Montly average electric production 2025 scenario 1

***Year 2035***

For year 2035 the current installed capacity is not able to meet Isabela's demand anymore. For this year, it is required to add an extra generator to power the island. Performing an iterative process, Homer suggest that an extra generator of at least 650 kW is required. New schematic of the system can be seen in figure 39.

Running the model the following results are obtained, figure 40 and table 7 . In figure 41 the average electric production of the different generators during the year is shown. It can be noticed that EXTRA generator is needed to supply power in the peak months march, april and december.Moreover figure 42 illustrates the behavior of the generators in the system, how they alternate, increase and decrease their power outputs to perfectly match demand without generating any extra energy (load following strategy).

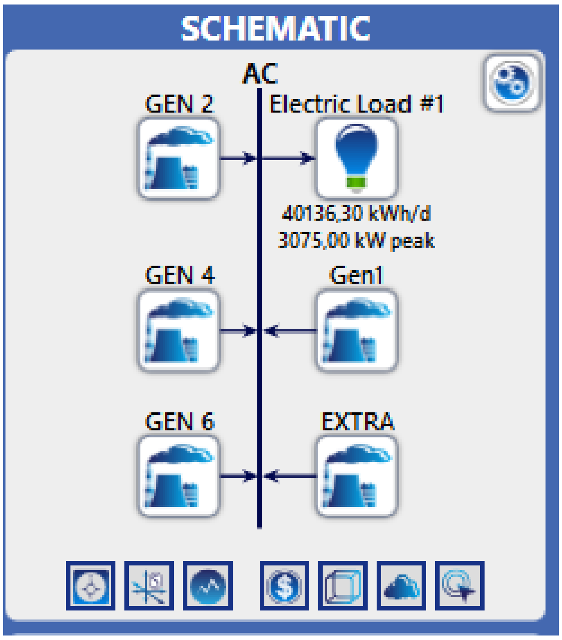



**Figure** 39: Isabela's thermal system scheme 2035 scenario 1

| Architecture | | | | | | Cost | | | |
|---|---|---|---|---|---|---|---|---|---|
| GEN 2 (kW) | GEN 4 (kW) | Gen1 (kW) | GEN 6 (kW) | EXTRA (kW) | | COE (€) | NPC (€) | Operating cost (€) | Initial cap (€) |
| 545 | 545 | 650 | 900 | 650 | LF | 0,227 € | 43,1 €M | 3,25 €M | 1,12 €M |

**Figure** 40: Simulation results 2035 Scenario 1

| | | RESULTS FOR 2035 | |
|---|---|---|---|
| **Name** | **Working Hours** | **Production (kWh)** | **Fuel (L)** |
| **GEN 1** | 4.409 | 2.682.476 | 758.910 |
| **GEN 2** | 8.159 | 2.592.142 | 736.313 |
| **GEN 4** | 5.924 | 1.005.323 | 310.921 |
| **GEN 6** | 8.760 | 7.819.581 | 2.018.354 |
| **GEN EXTRA** | 930 | 550.229 | 156.134 |
| | **Total** | 12.235.751 kWh | 3.980.632 L |

**Table** 7: Homer Results 2035 scenario 1

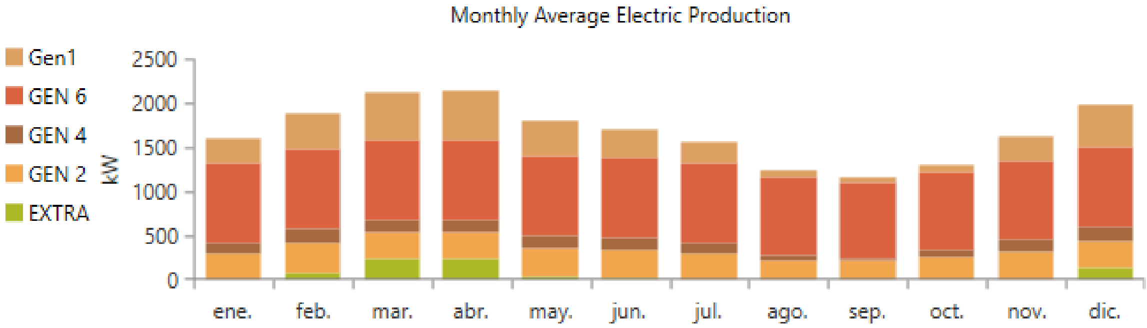



**Figure** 41: Montly average electric production (kW vs months) 2035 scenario 1

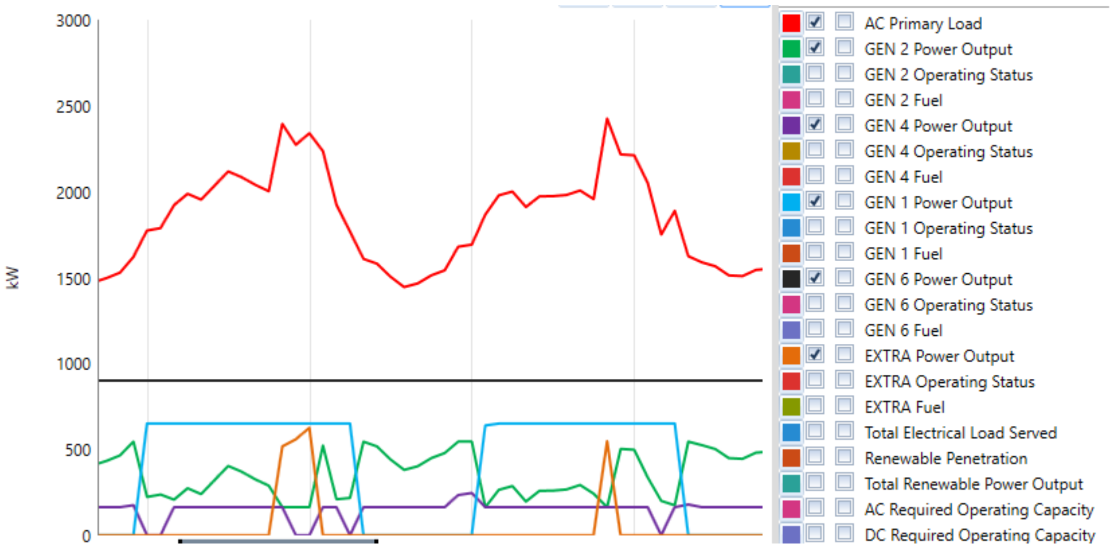



**Figure** 42: Generators behavior vs primary load 2035 scenario 1

### 5.1.2. Summary and analysis of results Scenario 1

In order to have a general view of Scenario 1, a summary of results is arranged in figure 43.

| SUMMARY SCENARIO 1 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| YEAR | CAPACITY INSTALLED (Kw) | ENERGY PRODUCTIO N (MWh) | LCOE (€/kWh) | NPC (M€) | O&M COST (M€) | INITIAL INV (M€) | FUEL (L) | CO2 EMISSIONS (Kg/yr) |
| 2015 | 2.640 | 4.899 | 0,231 | 14,7 | 1,06 | 0,92 | 1.320.143 | 3.462.146 |
| 2020 | 2.640 | 7.339 | 0,226 | 21,5 | 1,59 | 0,92 | 1.963.459 | 5.154.402 |
| 2025 | 2.640 | 9.773 | 0,225 | 28,4 | 2,13 | 0,92 | 2.623.029 | 6.890.107 |
| 2035 | 3.290 | 12.236 | 0,227 | 43,1 | 3,25 | 1,12 | 3.980.632 | 10.453.983 |

**Figure** 43: Summary of results scenario 1

As the demand increases throughout the years, the energy production and thus the amount of fuel consumed, increase as well. The increase in fuel consumption not only implies largest amounts of carbon dioxide emissions to the atmosphere but also increases the probability of fuel pouring to the ocean, fact that could have catastrophic effects in the ecosystem. As it can be seen in figure 44 nearly 10.5 million kg of Carbon Dioxide will be released to the atmosphere.

Initial installed capacity of 2.640 kW is able to meet the rising demand of Isabela up to year 2025, by increasing the working hours and energy production of the available generators, but later in 2035 another generator is required for the system. Allowing Homer to size this extra generator, it is concluded that a new one of at least 650 kW has to be added to meet the demand. Therefore up to year 2025 the initial investment of the project is the same, 0,92 M €, what increases throughout the years is the operation and maintenance (O&M) cost, due to the largest working hours and maintenance associated, and thus the total Net present cost (NPC) of the project. In 2035, due to the extra generator, the initial investement goes up to 1,12 million €. LCOE (as mentioned in previously although Homer names it COE it stands for Levelized COE) just varies few cents along the years. The variations in the cost of the project are better illustrated in figure 45.

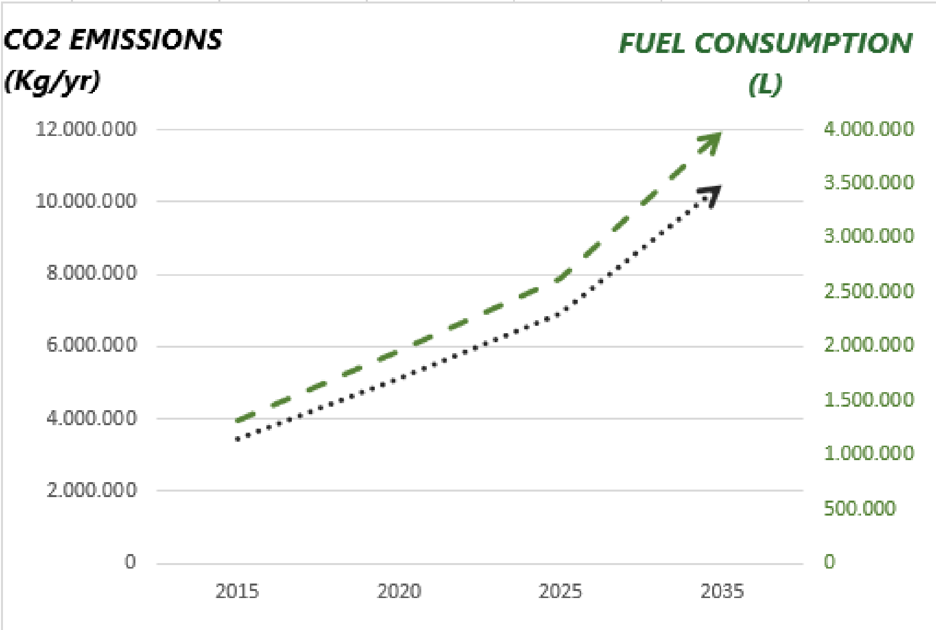



**Figure** 44: Isabela's Fuel and emissions evolution Scenario 1

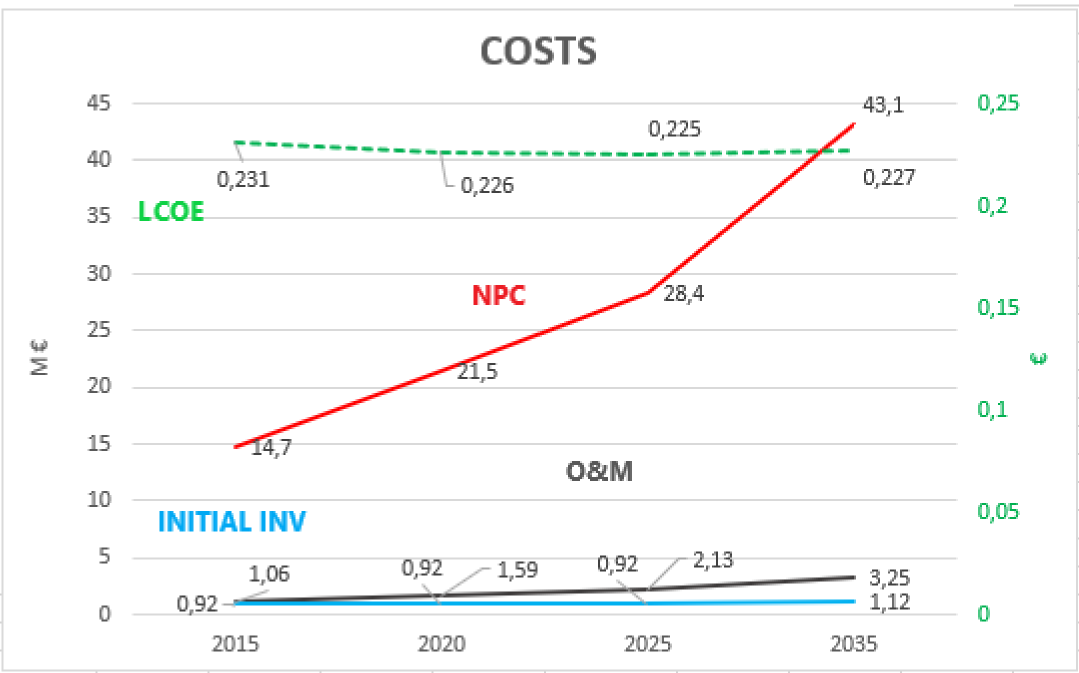



**Figure** 45: Isabela's evolution of costs Scenario 1: LCOE, Initial investment, NPC and O&M

## 5.2. Scenario2: Hybrid System original design: 25 % of renewable energy penetration

### 5.2.1. Simulations

For the second scenario, the Hybrid system planned for Isabela is going to be simulated with the specifications shown in table 3. Although the operation of the Hybrid system is expected to begin in 2018, for this thesis it is assumed that the Hybrid system started to operate in 2015, however since no real data is known, is not possible to validate this model. In this scenario, PV pannels, generators and batteries work simultaneously to meet the demand and the capacity installed is going to be modified over time to keep the same percentage of renewable energy penetration.

***Year 2015***

The specifications of PV pannels, generators, batteries and converter of the designed Hybrid system by ELECGALAPAGOS are introduced in Homer to simulate the first year of this scenario. To simplify the model, one single generator of 1.625 kW is used instead of five small generators of 325 kW each, and PV pannels are considered to be attached to the AC side. Load following control strategy is selected for the simulations. In load following strategy, Diesel generators instead of working at full capacity only provide enough power to meet the demand and batteries are charged with extra kW produced by solar energy. This control strategy prioritizes renewable energy while decreasing fuel consumption. Once the schematic is built 46 the model is run and the results shown in figure 47 are obtained. With this configuration, the system can provide around 25 % of renewable energy penetration and this percentage will be maintained for the following years.

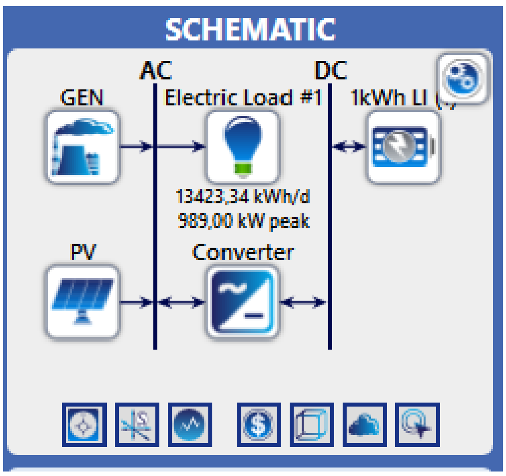



**Figure** 46: Scheme of the Isabela's original designed Hybrid system

| Architecture | | | | | Cost | | | System |
|---|---|---|---|---|---|---|---|---|
| PV (kW) | GEN (kW) | 1kWh LI (1) | Converter (kW) | | COE (€) | NPC (€) | Initial cap (€) | Ren Frac (%) |
| 922 | 1.625 | 258 | 833 | LF | 0,266 € | 16,8 €M | 3,66 €M | 25,2 |

**Figure** 47: Simulation results 2015 scenario 2

Figure 48 displays PV power output data. The left axis represents the hours of the day, where it can be noticed that there is solar output from 6 am to 6 pm approximately, and the right axis represents the output power with a color range. Around noon time, when the sun rays are perpendicular to the surface of the PV pannel, more energy is produced than at times closer to sunrise or sunset due to the location of the sun. Moreover figure 49 allows to understand the functioning of the different components that make up the hybrid system. Line color *red* represents the AC primary load, line *blue* the generator output power, line *yellow* the PV output power and color *purple* the batteries discharge power. During day time and whenever the environmental conditions are suitable, solar energy is produced by the PV pannels and the system prioritizes its integration. If PV pannels can provide enough power to meet the load the generator is turned off, however when there is not enough solar output or it is night time, the generator is started. At night time, the generator only produces the exact amount of energy to meet the load, which corresponds to the load following strategy behavior explained above. Another feature that can be seen is that batteries start to work when solar output can not completely meet the load but is still high enough to not have the need to start a generator, cause as previously said, generators have a minimum load start ratio.

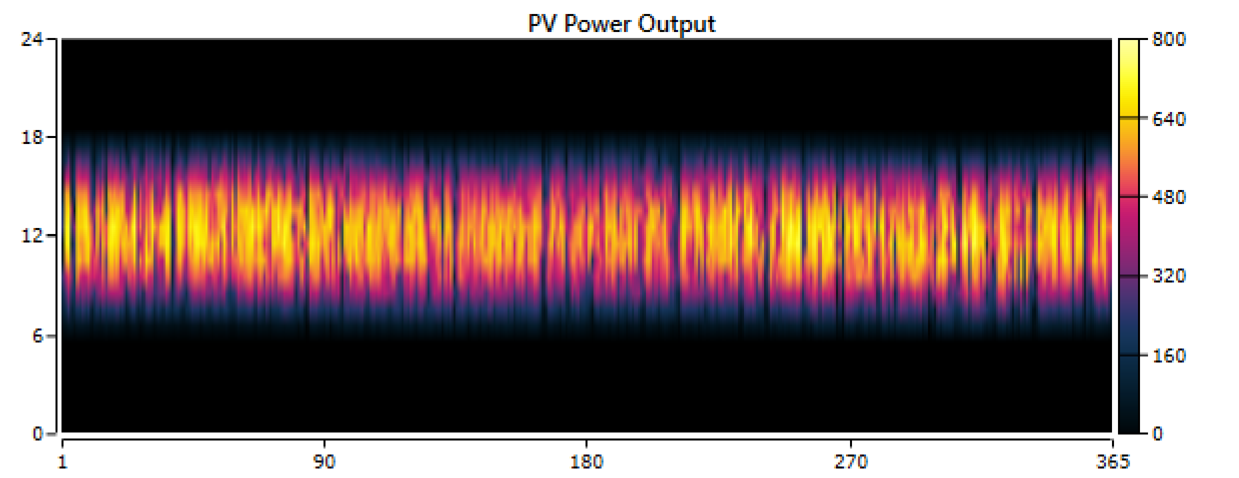



**Figure** 48: Solar PV Power Output color range

***Year 2020***

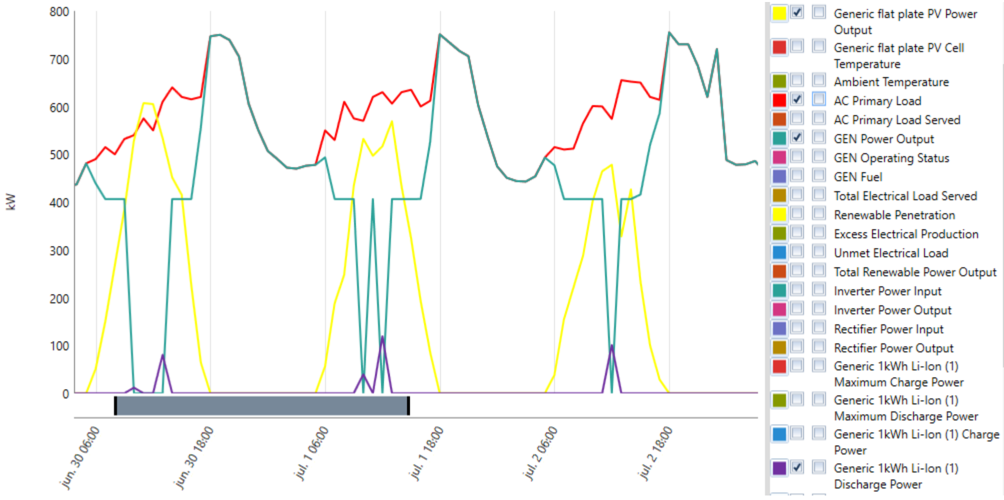



**Figure** 49: PV, generator output and primary load behavior 2015 scenario 2

In year 2020, as the demand has increased, the current installed capacity is not able to meet the load with a 25 % renewable penetration and therefore has to be modified. By means of an iteration process, it is concluded that it is required to increase the PV capacity up to 1.230 kW while the rest of the components remain the same. Results can be seen in figure 50. Regarding the electrical behavior, the functioning is still similar to year 2015.

| Architecture | | | | | Cost | | | System |
|---|---|---|---|---|---|---|---|---|
| PV (kW) | GEN (kW) | 1kWh LI | Converter (kW) | | COE (€) | NPC (€) | Initial cap (€) | Ren Frac (%) |
| 1.230 | 1.625 | 258 | 833 | LF | 0,286 € | 27,1 €M | 4,74 €M | 25,0 |

**Figure** 50: Simulation results 2020 scenario 2

***Year 2025***

In year 2025 the demand has grown sufficiently to have significant changes in the model. Now both solar PV and Diesel capacity have to increase to meet the load while satisfying the restriction of 25 % of renewable penetration. An autosize generator is added to the scheme for Homer to decide which is the extra capacity required. After running the simulations, the final configuration is shown in figure 51. PV capacity increased up to 1.440 kW and an extra generator of 640 kW needs to be added to the system, providing a total amount of 2.265 kW of diesel thermal energy.

Figures 52 and 53 are displayed to understand the functioning of the system with the extra generator added and the whole behavior of the batteries in the system.

| Architecture | | | | | | Cost | | | System |
|---|---|---|---|---|---|---|---|---|---|
| PV (kW) | GEN (kW) | EXTRA GEN (kW) | 1kWh LI | Converter (kW) | Dispatch | COE (€) | NPC (€) | Initial cap (€) | Ren Frac (%) |
| 1.440 | 1.625 | 640 | 258 | 833 | LF | 0,238 € | 30,0 €M | 5,47 €M | 25,0 |

**Figure** 51: Simulation results 2025 scenario 2

In figure 52 line *red* is the AC load, line *yellow* the PV solar output power, line *blue* the first generator output power and line *green* the extra generator output power. When there is no solar output, the first generator (*blue*) meets the load completely. During day time, solar energy meets the load and when solar output is not enough, Extra generator (*green*) is started so together with the PV pannels can supply enough power to meet the demand.

Figure 53 is composed of two graphs. In the upper graph AC load, Solar output and batteries charge (color *pink*) and discharge (color *purple*) powers are plotted. On the one hand, when Solar output is higher than the load, that extra energy produced is used to charge the batteries and store the extra energy. On the other hand, when solar output is insufficient, batteries discharge the power previously stored to help to meet the load. In the lower graph, the state of charge (color *green*), charge and discharge powers are plotted together. The state of charge of the batteries is illustrated as an horizontal line that increases and decreases, where its value is represented in percentage ( left axis). When the batteries charge (represented by a pink spike) it goes up to a maximim level of 100 % , but when batteries discharge power (represented by a purple spike) it starts to drop up to a minimum level of 25 %, this level is set by defautl. The state of charge represents in percentage values the amount of energy stored inside the batteries at every time step.

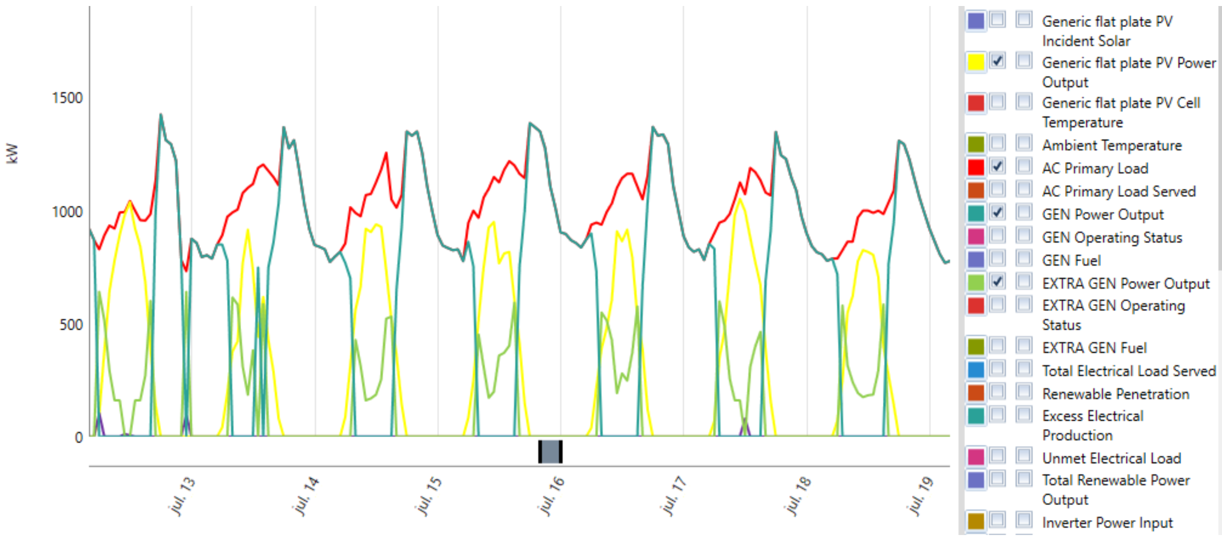



**Figure** 52: Functioning of PV, generator and EXTRA generator 2025 scenario 2


**Figure** 53: Batteries state of charge, charge and discharge powers 2025 scenario 2

***Year 2035***

The last year of study is 2035, where the capacity of the components needs to be adjusted again. Performing and iteration process, the following results are obtained with Homer 54. In this case the capacity of all the components has to increase, PV installed capacity is now 2.200 kW, Total diesel installed capacity accounts for 3.025 kW and 350 kWh of batteries.

| Architecture | | | | | | Cost | | | System |
|---|---|---|---|---|---|---|---|---|---|
| PV (kW) | GEN (kW) | EXTRA (kW) | 1kWh LI | Converter (kW) | | COE (€) | NPC (€) | Initial cap (€) | Ren Frac (%) |
| 2.200 | 1.625 | 1.400 | 350 | 833 | LF | 0,228 € | 43,3 €M | 8,27 €M | 25,2 |

**Figure** 54: Simulation results 2035 scenario 2

### 5.2.2. Summary and analysis of results Scenario 2

Figure 55 summarizes the resuls obtained for all the years simulated in scenario 2. As time passes by, demand increases and thus the capacity installed, always keeping a 25 % of renewable energy penetration that is the main objective of this scenario. To analyse the behavior of the different parameters during the time frame of the study, graphics are created in excel.

Graphic 56 shows the correlation between fuel usage and carbon dioxide emissions, the larger the diesel installed capacity, the more liters of fuel are required and thus

| SUMMARY SCENARIO 2 | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| YEAR | CAPACITY INSTALLED (kW) | | ENERGY PRODUCTION (MWh) | LCOE (€/kWh) | NPC (M€) | INITIAL INV (M€) | RENEWABLE ENERGY (%) | FUEL (L) | CO2 EMISSIONS Kg/yr |
| 2015 | DIESEL | 1.625 | 3.665 | 0,266 | 16,8 | 3,66 | 25 | 1.059.057 | 2.778.371 |
| | SOLAR PV | 922 | 1.589 | | | | | | |
| | BATTERIES | 258 kWh, 833 kW | 52,3 | | | | | | |
| 2020 | DIESEL | 1.625 | 5.501 | 0,286 | 27,1 | 4,74 | 25 | 1.752.721 | 4.584.386 |
| | SOLAR PV | 1.230 | 2.120 | | | | | | |
| | BATTERIES | 258 kWh, 833 kW | 20,3 | | | | | | |
| 2025 | DIESEL | 2.265 | 7.328 | 0,238 | 30 | 5,47 | 25 | 1.961.721 | 5.142.533 |
| | SOLAR PV | 1.440 | 2.482 | | | | | | |
| | BATTERIES | 258 kWh, 833 | 13 | | | | | | |
| 2035 | DIESEL | 3.025 | 10.960 | 0,228 | 43,3 | 8,27 | 25 | 2.893.336 | 7.586.980 |
| | SOLAR PV | 2.200 | 3.792 | | | | | | |
| | BATTERIES | 350 kWh, 833 kW | 17 | | | | | | |

**Figure** 55: Summary of results scenario 2

the more emissions are released. Left axis represents the amount of emission in kg/yr and right axis the fuel consumption in liters. By year 2035 it is required to use aprox. 2.8 million Liters of fuel that translated into nearly 7.5 millions of kg of carbon dioxide released to the atmosphere. The last graph 57 shows the correlation between intial investment and net present cost of the project. As capacity installed rises, the higher the initial investment and thus the NPC of the project. LCOE that measures the costs over usuful energy over the lifetime of the project (€/kW), varies few cents among the years. In this scenario the variation, although is few cents, is larger than in the previous case, with a peak in 2020.

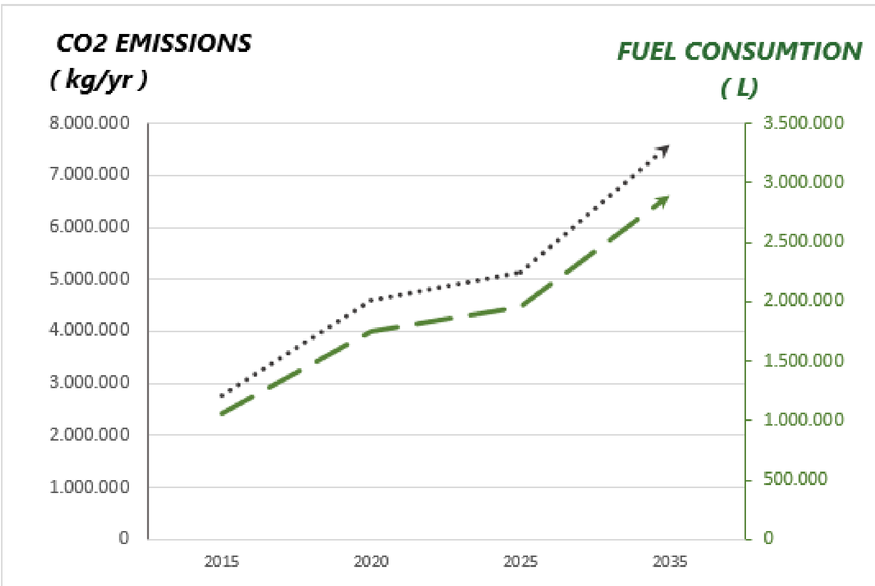



**Figure** 56: Isabela's Fuel and emissions evolution scenario 2

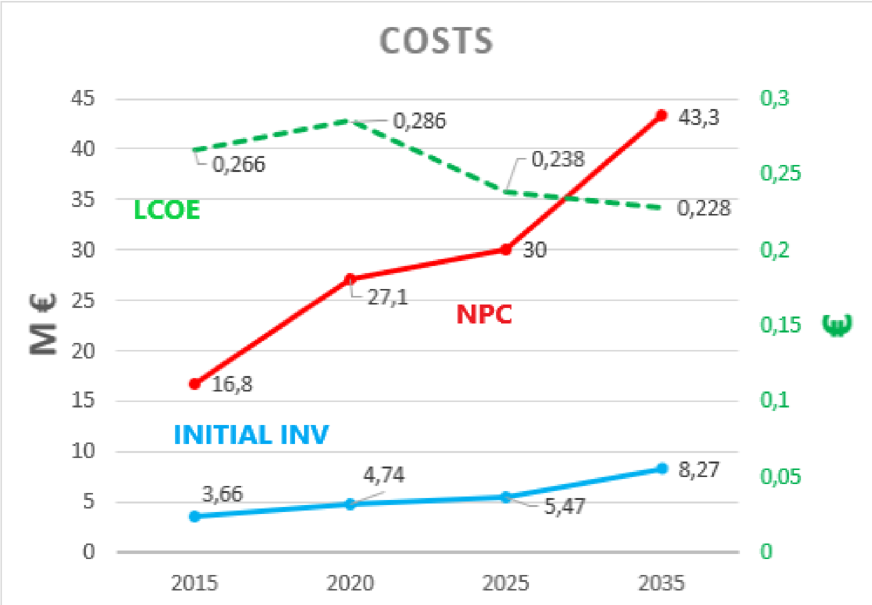



**Figure** 57: Isabela's original Hybrid system costs evolution scenario 2

## 5.3. Scenario 3: Hybrid System with 50 % of renewable energy penentration

### 5.3.1. Simulations

The main objective of the following simulations is to keep a 50 % of renewable energy penetration and see the evolution of the system over the time.

***Year 2015***

Introducing the demand for 2015 and the restriction of 50 % of renewable energy penetration, Homer is the one sizing the capacity of the components. The following results are obtained 58. It can be noticed that PV and batteries installed capacity is considerably higher than Diesel's.
Figure 59 displays the behavior of the components. As stated in previous simulations, during day-time PV Output power meets the demand and at night-time or non-solar days, generators and batteries do it.

| Architecture | | | | | Cost | | | System |
|---|---|---|---|---|---|---|---|---|
| PV (kW) | Gen (kW) | 1kWh LI (1) | Converter (kW) | | COE (€) | NPC (€) | Initial cap (€) | Ren Frac (%) |
| 1.921 | 1.100 | 1.797 | 833 | LF | 0,275 € | 17,4 €M | 7,53 €M | 50,0 |

**Figure** 58: Simulation results 2015 scenario 3

At this point, figure 60 displays this information in another way with a color range. Three images integrate the figure, the first one displays PV Power Output,

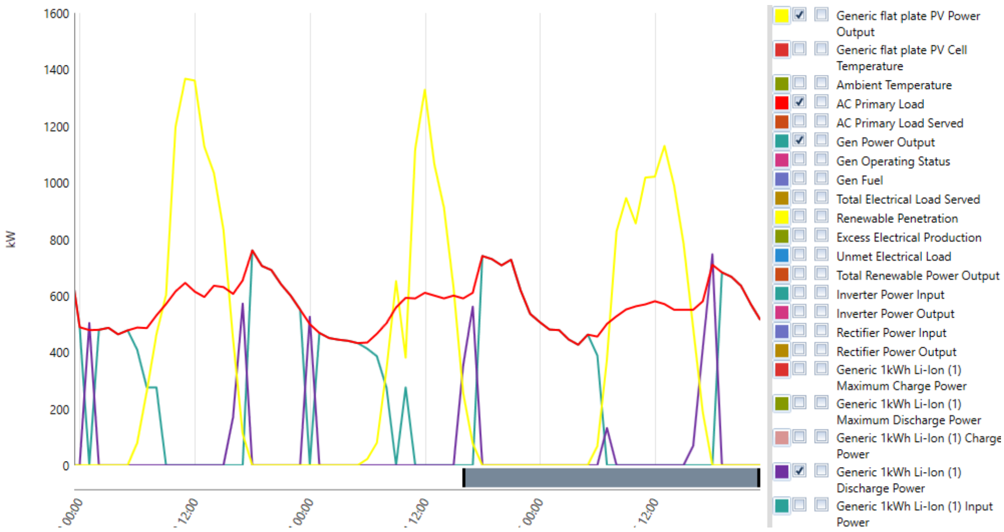



**Figure** 59: Components behavior 2015 scenario 3

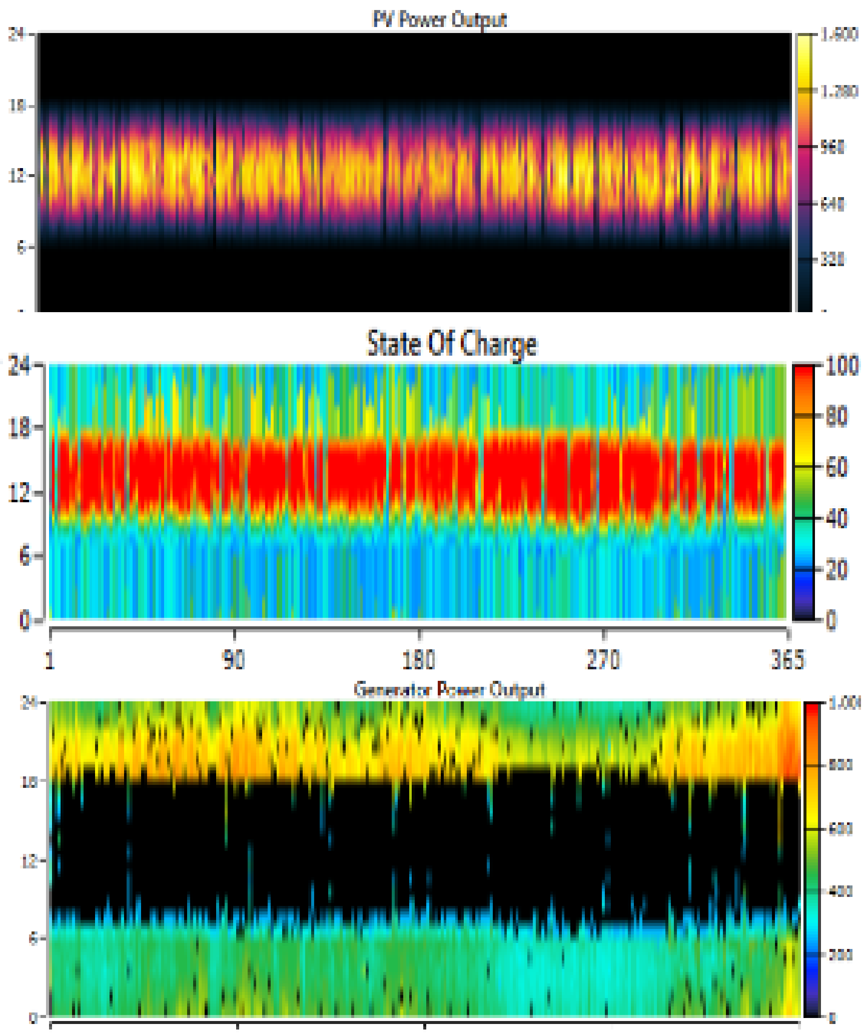



**Figure** 60: PV Output, State of charge and Generator Output color graphs

the second the State of Charge of the batteries and the third one the Generator Power Output. It can be noticed that there is a correlation among them cause they present a thick line in the middle of them. In the first one, the power output ranges from yellow to black, from maximum to minimum output. There is output power from 6 am to 6 pm with higher values near noon time.
In the second picture, the state of charge of the batteries ranges from red (maximum state of charge) to black (zero state of charge). First of all it can be seen that color never goes bellow light blue in the scale, which means that the minimum state of charge allowed is 25 %. Approximattely from 10am to 6pm the state of charge is maximum and it matches the time that there is solar output and batteries are charged, however at the other hours batteries are discharging power and that is why color decreases up to blue. The third image shows that during the hours that there is solar output, the output power of the generator is near to zero but at night time generator is functioning and delivering power. This whole figure represents the functioning and alternance of the components in the system.

***Year 2020***

Introducing the demand calculated for year 2020, Homer gets to the conclusion that the optimized model with lowest NPC is the one shown in figure 61. To meet the rising the demand, the capacity installed of all the components increases but as 50 % of renewable penetration is required, capacity of PV and batteries is larger than diesel's.

| Architecture | | | | | Cost | | | System |
|---|---|---|---|---|---|---|---|---|
| PV (kW) | Gen (kW) | 1kWh LI | Converter (kW) | | COE (€) | NPC (€) | Initial cap (€) | Ren Frac (%) |
| 2.543 | 1.700 | 3.446 | 1.064 | LF | 0,270 € | 25,6 €M | 10,7 €M | 50,0 |

**Figure** 61: Simulation results 2020 scenario 3

***Year 2025***

Running the simulation the following results are obtained, figure 62. Capacity installed keeps on increasing to meet the rising demand. The electrical behavior is similar to previous years.

***Year 2035***

For the last year this simualtion is going to be done for, results obtained are displayed in figure 63. Components are adjusted in such a way that there is always a 50 % of renewable penetration.

| Architecture | | | | | Cost | | | System |
|---|---|---|---|---|---|---|---|---|
| PV (kW) | Gen (kW) | 1kWh LI | Converter (kW) | | COE (€) | NPC (€) | Initial cap (€) | Ren Frac (%) |
| 3.352 | 2.300 | 4.732 | 1.169 | LF | 0,269 € | 33,9 €M | 14,2 €M | 50,0 |

**Figure 62**: Simulation results 2025 scenario 3

| Architecture | | | | | Cost | | | System |
|---|---|---|---|---|---|---|---|---|
| PV (kW) | Gen (kW) | 1kWh LI | Converter (kW) | | COE (€) | NPC (€) | Initial cap (€) | Ren Frac (%) |
| 5.053 | 3.400 | 6.977 | 1.913 | LF | 0,268 € | 50,7 €M | 21,3 €M | 50,1 |

**Figure 63**: Simulation results 2035 scenario 3

### 5.3.2. Summary and analysis of results scenario 3

Results obtained from the different years simulated are arranged in table 64 for an easier comparison. As in the previos scenarios, the increase of energy demanded makes the capacity installed to increase as well. As in this scenario the goal is to have a system with 50 % of renewable penetration, capacity comming from renewable sources is higher that Diesel's. As one might expect, the higher the capacity installed, the higher the initial investment required to buy the components and the higher the Net present cost (NPC) of the project. However it can be seen in the data that the levelized cost of energy (LCOE) decreases few cents. To see the evolution of the costs in the project, figure 65 is created.

| SUMMARY SCENARIO 3 | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| YEAR | CAPACITY INSTALLED (kW) | | ENERGY PRODUCTION (MWh) | LCOE (€/kWh) | NPC (M€) | INITIAL INV (M€) | RENEWABLE ENERGY (%) | FUEL (L) | CO2 EMISSIONS Kg/yr |
| 2015 | DIESEL | 1.100 kW | 2.450 | 0,275 | 17,4 | 7,53 | 50 | 669.812 | 1.831.838 |
| | SOLAR PV | 1.921 kW | 3.311 | | | | | | |
| | BATTERIES | 1.797 kWh, 833 kW | 449,0 | | | | | | |
| 2020 | DIESEL | 1.700 kW | 3.668 | 0,27 | 25,6 | 10,7 | 50 | 1.042.829 | 2.729.725 |
| | SOLAR PV | 2.543 kW | 4.384 | | | | | | |
| | BATTERIES | 3.446 kWh, 1.064 kW | 789,0 | | | | | | |
| 2025 | DIESEL | 2.300 kW | 4.885 | 0,269 | 33,9 | 14,2 | 50 | 1.381.362 | 3.615.873 |
| | SOLAR PV | 3.352 kW | 5.778 | | | | | | |
| | BATTERIES | 4.732 kWh, 1.169 kW | 1.071 | | | | | | |
| 2035 | DIESEL | 3.400 kW | 7.312 | 0,268 | 50,7 | 21,3 | 50 | 2.053.995 | 5.376.659 |
| | SOLAR PV | 5.053 kW | 8.709 | | | | | | |
| | BATTERIES | 6.970 kWh, 1.913 kW | 1.601 | | | | | | |

**Figure 64**: Summary of results scenario 3

Another fact that can be noticed is that as energy produced in the genertors increases, the fuel usage increases and more emission are released to the atmosphere, however as renewable penetration percentage is higher, pollution is lower. 66

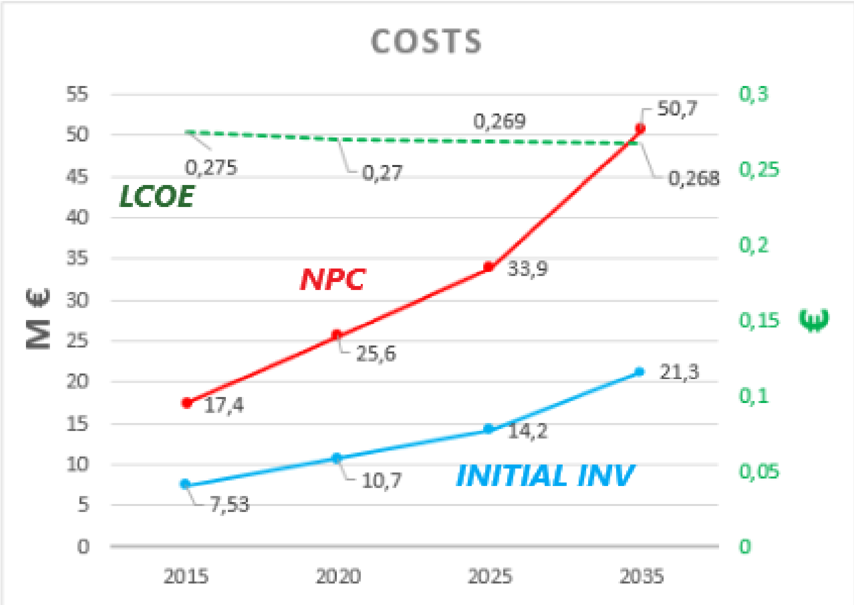



**Figure** 65: Isabela's evolution of costs scenario 3

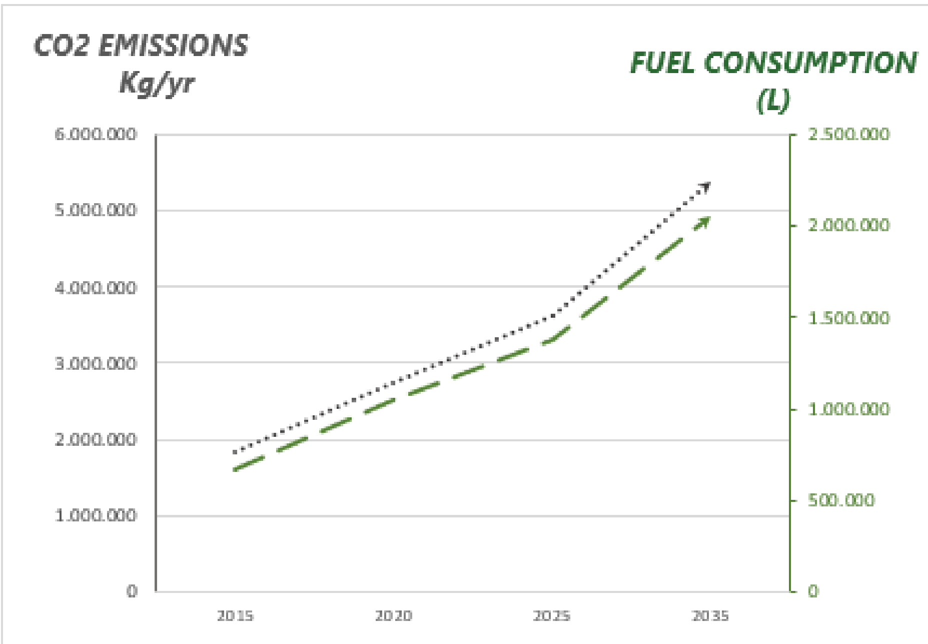



**Figure** 66: Isabela's fuel and emissions evolution Scenario 3

## 5.4. Scenario 4: Hybrid System with 75 % of renewable energy penetration

For this new scenario, the objective is to see the evolution of the system while keeping a renewable penetration of 75 %.

### 5.4.1. Simulations

***Year 2015***

Allowing Homer to redimensionate the system according to the requirements selected, the results obtained are displayed in 67.
As mentioned earlier, the PV Outoput Power depends on many factors including the angle of incidence that tracks the position of the sun respect to the surface of the pannel. In figure 69 it is plotted the PV Power output (*yellow*) and the PV Angle of incidence (*purple*). The incidence angle in a PV pannel is the angle between the normal to the surface and the solar radiation, shown in figure 68. When the angle of incidence is 0°the sun is perpendicular to the surface and when it is 90°is parallel to it. Now the concept is introduced, it can be seen in the graph, looking at the right axis, that when incidence angle 90°there is no solar output cause sun is parallel to the pannel, however when it is 0°the solar power output is maximum. The position of the sun, thus the incidence angle, determines the amount of power output that is produced.

| Architecture | | | | | Cost | | | System |
|---|---|---|---|---|---|---|---|---|
| PV (kW) | Gen (kW) | 1kWh LI (1) | Converter (kW) | | COE (€) | NPC (€) | Initial cap (€) | Ren Frac (%) |
| 2.500 | 1.100 | 7.188 | 1.003 | LF | 0,321 € | 20,3 €M | 12,6 €M | 75,1 |

**Figure** 67: Simulation results 2015 scenario 4

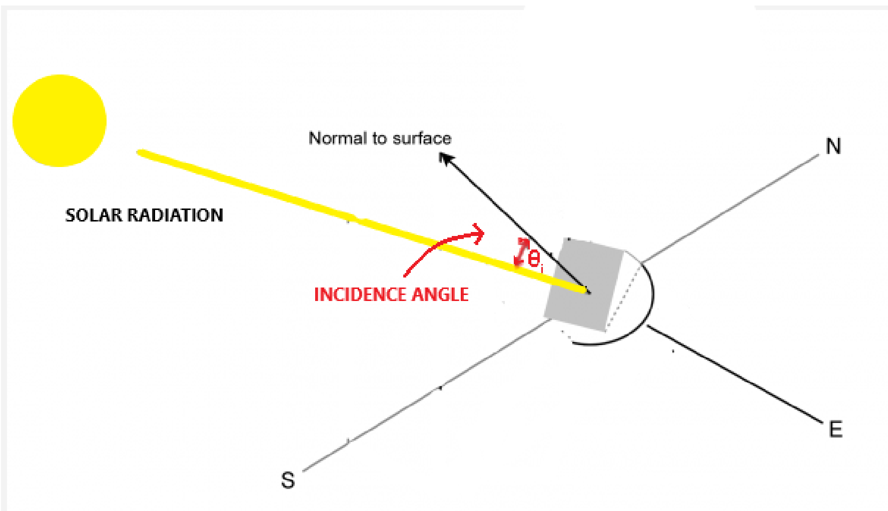



**Figure** 68: Incidence angle scheme

***Year 2020***

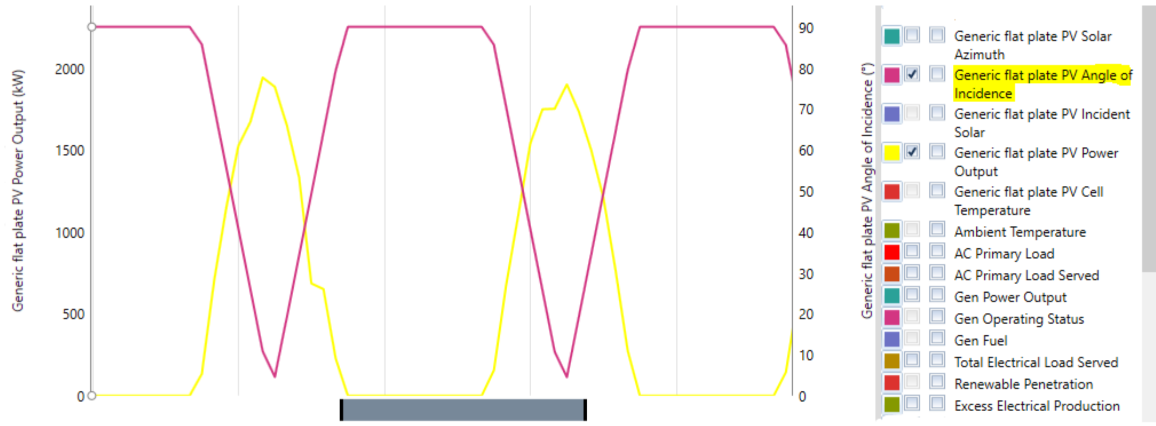



**Figure** 69: Incidence angle vs PV power output

Simulation for year 2020 shows, as it was expected, that capacity installed keeps on increasing, especially the capacity of the batteries. As the renewable penetration increases it is shown in the results that batteries start to play a significant role in the system.

| Architecture | | | | | Cost | | | System |
|---|---|---|---|---|---|---|---|---|
| PV (kW) | Gen (kW) | 1kWh LI (1) | Converter (kW) | | COE (€) | NPC (€) | Initial cap (€) | Ren Frac (%) |
| 3.808 | 1.700 | 10.842 | 1.366 | LF | 0,321 € | 30,5 €M | 19,0 €M | 75,0 |

**Figure** 70: Simulation results 2020 scenario 4

It can be seen in figure 71 that batteries are the ones meeting the load at non-solar hours, just receiving punctual help from the generator from time to time. That's the main reason why batteries capacity is increasing that much, they have to be able to store a big amount of extra solar kW and discharge them later when required.

***Year 2025***

Running the simulation, the new results obtained are shown in figure 72.

***Year 2035***

Results are shown in figure 74. For Scenario 4 the target is to simulate the models keeping a 75 % of renewable energy penetration. In figure 73 it is shown demand,

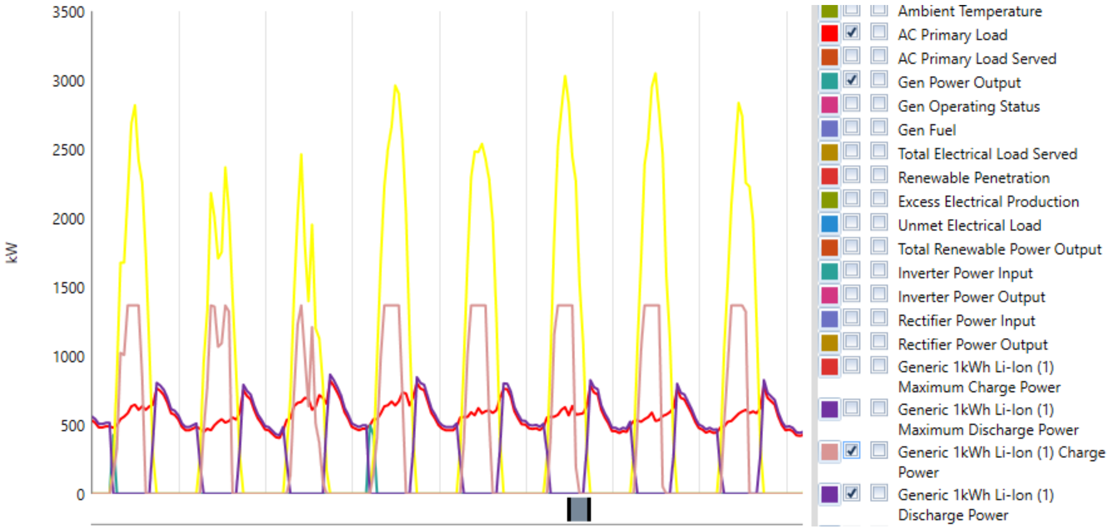



**Figure** 71: Components behavior 2020 scenario 4

| Architecture | | | | | Cost | | | System |
|---|---|---|---|---|---|---|---|---|
| PV (kW) | Gen (kW) | 1kWh LI (1) | Converter (kW) | Dispatch | COE (€) | NPC (€) | Initial capital (€) | Ren Frac (%) |
| 5.142 | 2.300 | 13.842 | 1.974 | LF | 0,322 € | 40,7 €M | 25,2 €M | 75,0 |

**Figure** 72: Simulation results 2025 scenario 4

solar output and generator output. The black circle enclose the period of the year with lower demand. Renewable output can cover the demand with a little support from generators.

| Architecture | | | | | Cost | | | System |
|---|---|---|---|---|---|---|---|---|
| PV (kW) | Gen (kW) | 1kWh LI (1) | Converter (kW) | | COE (€) | NPC (€) | Initial cap (€) | Ren Frac (%) |
| 7.761 | 3.400 | 20.500 | 3.269 | LF | 0,322 € | 61,1 €M | 37,9 €M | 75,0 |

**Figure** 73: Output power 2035 scenario 4

### 5.4.2. Summary and analysis of results Scenario 4

Summary of results for Scenario 4 is displayed in table 75.
As in the other scenarios, the rise of demand throughout the years leads to an increase in capacity installed, energy production, intial investment and NPC, while COE is almost constant 77. As 25 % of the energy is still coming from fossil fuels, there is still demand of fuel and thus emissions of green house gasses 76. As 75 % of the system works with renewable energy, the capacity of PV and batteries is larger that diesel's. The role of the batteries in the system starts to be more and more important, cause they are the ones supplying the power required when there is no solar output. The larger the capacity of the group batteries + converter, the

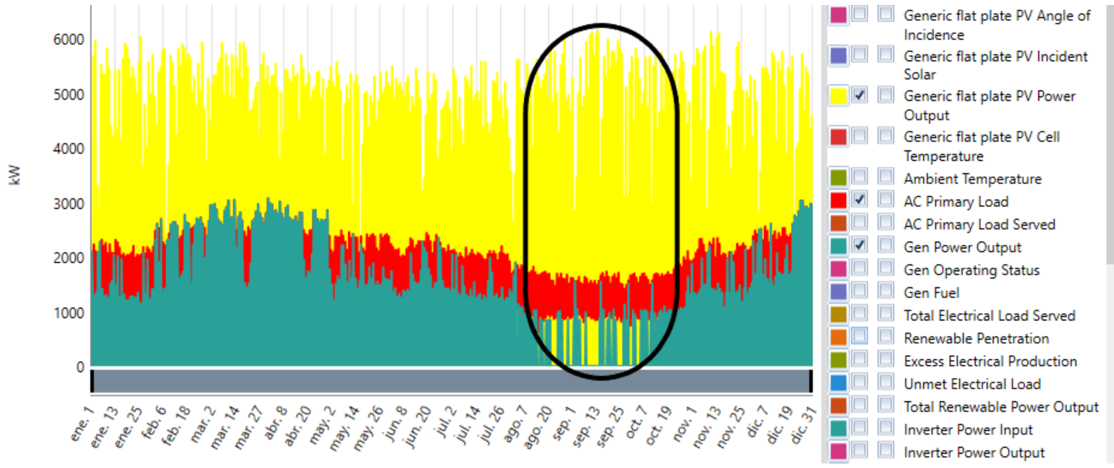



**Figure** 74: Simulation results 2035 scenario 4

| SUMMARY SCENARIO 4 | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| YEAR | CAPACITY INSTALLED (kW) | | ENERGY PRODUCTION (MWh) | LCOE (€/kWh) | NPC (M€) | INITIAL INV (M€) | RENEWABLE ENERGY (%) | FUEL (L) | CO2 EMISSIONS Kg/yr |
| 2015 | DIESEL | 1.100 kW | 1.222 | 0,321 | 20,3 | 12,6 | 75 | 353.331 | 924.884 |
| | SOLAR PV | 2.500 kW | 4.309 | | | | | | |
| | BATTERIES | 7.188 kWh, 1.003 kW | 1.684,0 | | | | | | |
| 2020 | DIESEL | 1.700 kW | 1.831 | 0,321 | 30,5 | 19 | 75 | 520.776 | 1.363.166 |
| | SOLAR PV | 3.808 kW | 6.565 | | | | | | |
| | BATTERIES | 10.842 kWh, 1.366 kW | 2.528,0 | | | | | | |
| 2025 | DIESEL | 2.300 kW | 2.441 | 0,322 | 40,7 | 25,2 | 75 | 694.511 | 1.817.963 |
| | SOLAR PV | 5.142 kW | 8.863 | | | | | | |
| | BATTERIES | 13.842 kWh, 1.974 kW | 3.358 | | | | | | |
| 2035 | DIESEL | 3.400 kW | 3.658 | 0,322 | 61,1 | 37,9 | 75 | 1.034.209 | 2.707.162 |
| | SOLAR PV | 7.761 kW | 13.377.303 | | | | | | |
| | BATTERIES | 20.500 kWh, 3.269 kW | 5.021 | | | | | | |

**Figure** 75: Summary of results scenario 4

lower the capacity of the generator has to be. In scenario 4, the generator only starts to work when batteries are not able to meet the load and an extra help is needed.

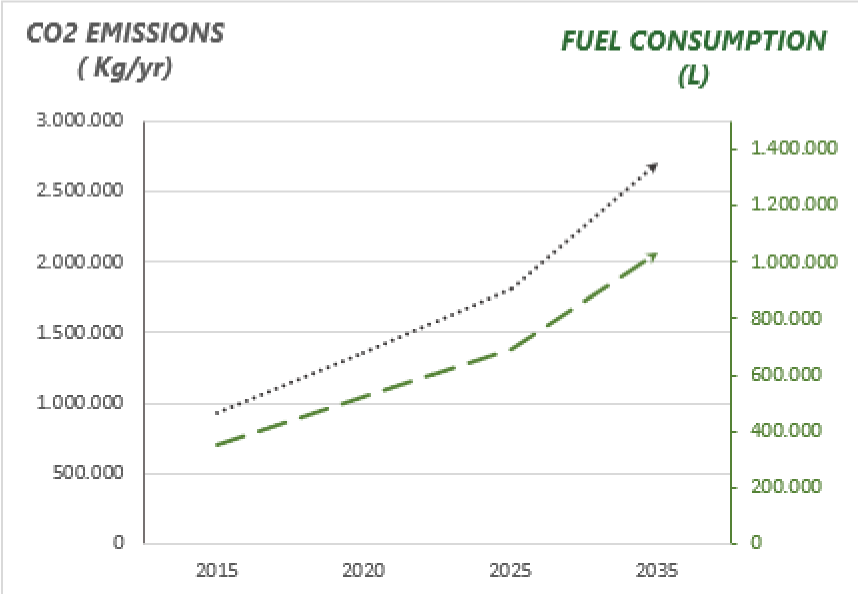



**Figure** 76: Fuel and Emissions Scenario 4

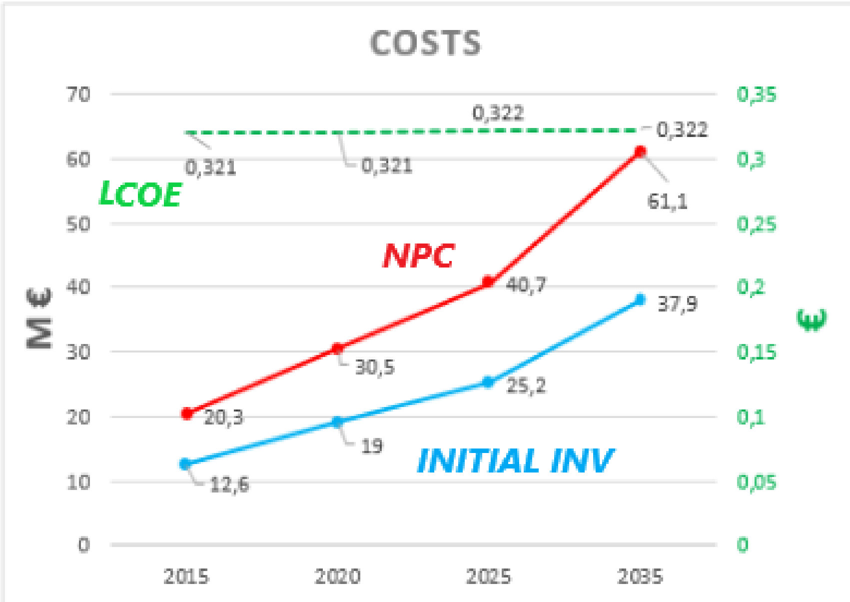



**Figure** 77: Costs scenario 4

## 5.5. Scenario 5: Hybrid system with a high level of renewable energy penetration

### 5.5.1. Simulations

***Year 2015***

Introducing the demand of 2015, selecting the components, control strategy and the restriction of 95 % of renewable energy penetration, Homer sizes the components and this time displays two different results sorted according to NPC value.78

The first result corresponds to a hybrid system composed of a Diesel generator, PV pannels and batteries that allow a renewable penetration of 95 %. The second possibility obtained is a completely renewable system powered with solar energy and batteries. Homer suggests that the best option is the first one cause it has a lower NPC.

| Architecture | | | | | Cost | | | System |
|---|---|---|---|---|---|---|---|---|
| PV (kW) | Gen (kW) | 1kWh LI (1) | Converter (kW) | | COE (€) | NPC (€) | Initial capi (€) | Ren Frac (%) |
| 3.563 | 1.100 | 11.822 | 1.447 | LF | 0,389 € | 24,6 €M | 18,7 €M | 95,2 |
| 5.114 | | 22.632 | 2.207 | LF | 0,602 € | 38,1 €M | 29,6 €M | 100 |

**Figure** 78: Simulation results 2015 Scenario 5

Although the difference in penetration is only a 5 % it has significant changes in the model both in installed capacity and cost. The PV, batteries and converter installed capacity have to increase nearly a 40 % to cover that 5 % different and this results in a huge difference in the initial investment, cost of energy and thus the net present cost of the project. Figures 79, 80 and 81 are displayed to see this difference.

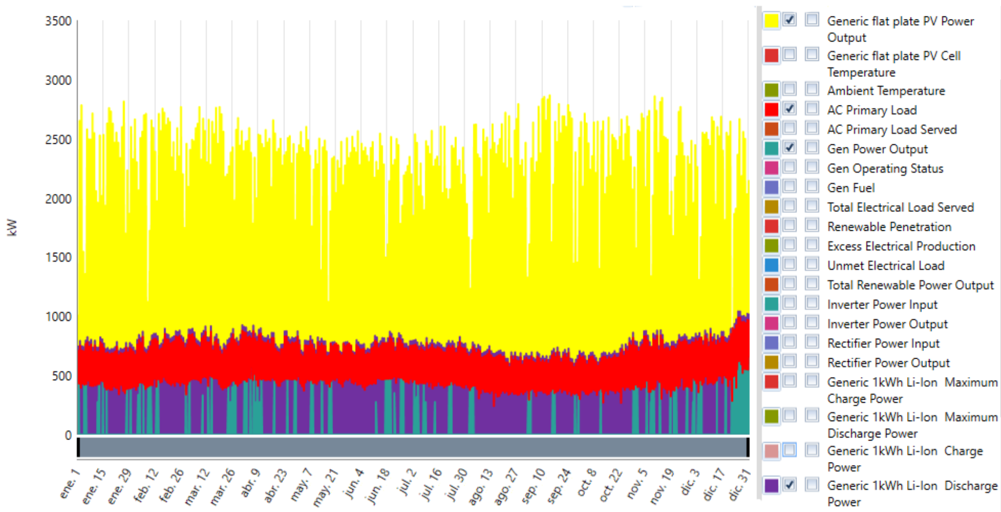



**Figure** 79: Solar Output power and Gen Output Power with 95 percent penetration 2015 scenario 5

Figure 79 corresponds to the 95 % penetration option. Demand is mainly covered by solar output (*yellow*) and batteries discharge power (*red*) and the scattered *blue* lines corresponds to the generator output. The power supplied by the generator in this system is minimum and it is only turned on during off-solar periods when the energy previously stored in the batteries is not enough to cover the whole demand. Figure 80 shows a more detailed view of the behavior of the components in the 95 % penetration option. During day time, solar energy meet the demand and

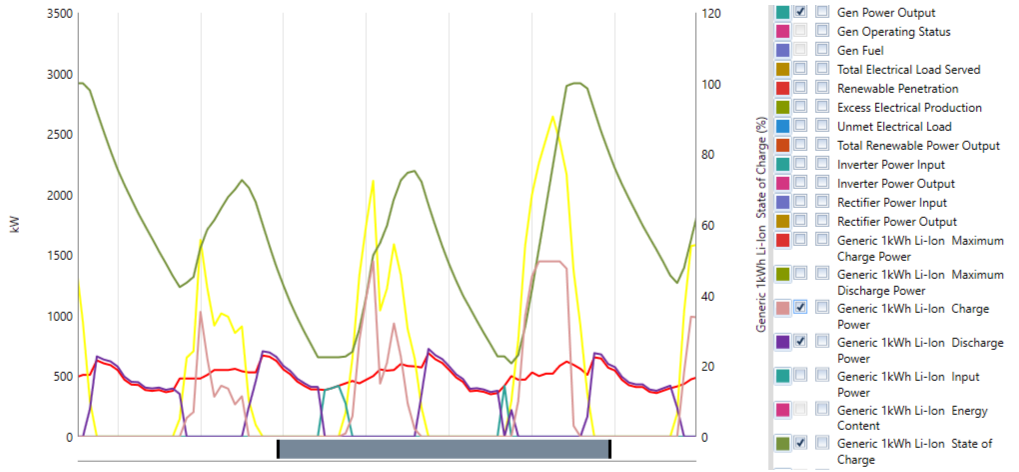



**Figure** 80: PV, Generator and batteries behavior with 95 percent renewable penetration 2015

the extra energy is stored in the batteries (*pink*) for a later discharge at off-sun hours. Line *green* shows the state of charge of the batteries, and when batteries are discharging power and it reaches the minimum discharge value of 25 % percent, generator is started to cover that small amount of load left and as soon as it does its function it is turned of right away. So as shown in the figures, generator's function is to cover punctual amounts of load.

Figure 81 represent the completely renewable system. This time as there is no emergency generator available, the capacity of both PV and batteries has be scaled up considerably. Batteries have to have enough storage capacity to completely meet the load at night time and if ever there are days where less PV output is obtained (as shown in the right side of the figure).

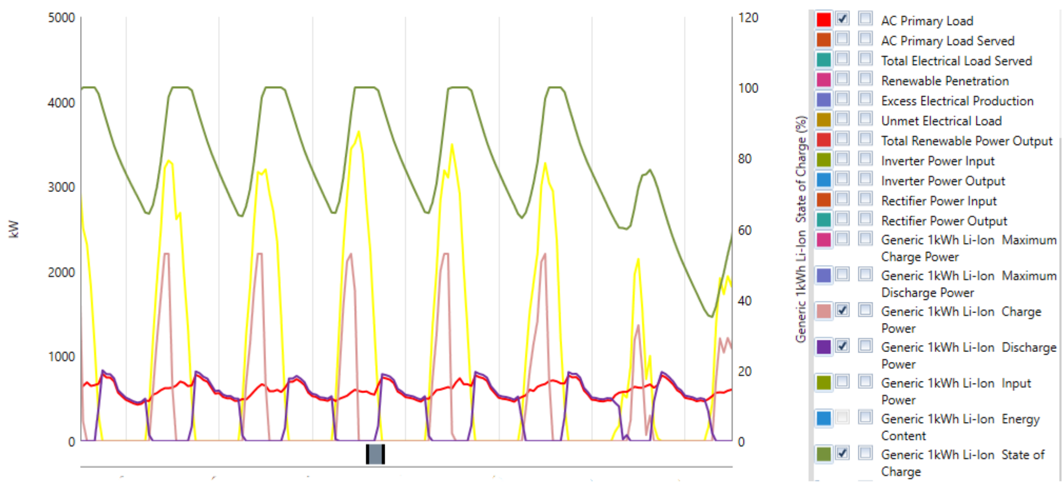



**Figure** 81: PV, Generator and batteries behavior with 100 percent renewable penetration 2015

### *Year 2020*

As in the previous simulation, in 2020 two results with a 95 % and a 100 % of renewable penetrations are displayed 82 . Again it can be seen a huge difference required in components' capacity installed and costs associated to the project. As said before, the higher the renewable penetration the higher the excess of electrical production. Figures 83 and 84 show the excess of electrical production, color *black*. Again only a 5 % difference translates into a huge difference of energy wasted, being the excess energy in the 100 % option sometimes even greater than the energy stored in the batteries.

| Architecture | | | | | Cost | | | System |
|---|---|---|---|---|---|---|---|---|
| PV (kW) | Gen (kW) | 1kWh LI (1) | Converter (kW) | | COE (€) | NPC (€) | Initial cap (€) | Ren Frac (%) |
| 5.590 | 1.700 | 18.306 | 2.906 | LF | 0,403 € | 38,3 €M | 29,3 €M | 95,1 |
| 8.206 | | 34.191 | 3.590 | LF | 0,624 € | 59,1 €M | 46,2 €M | 100 |

**Figure** 82: Simulation results 2020 Scenario 5

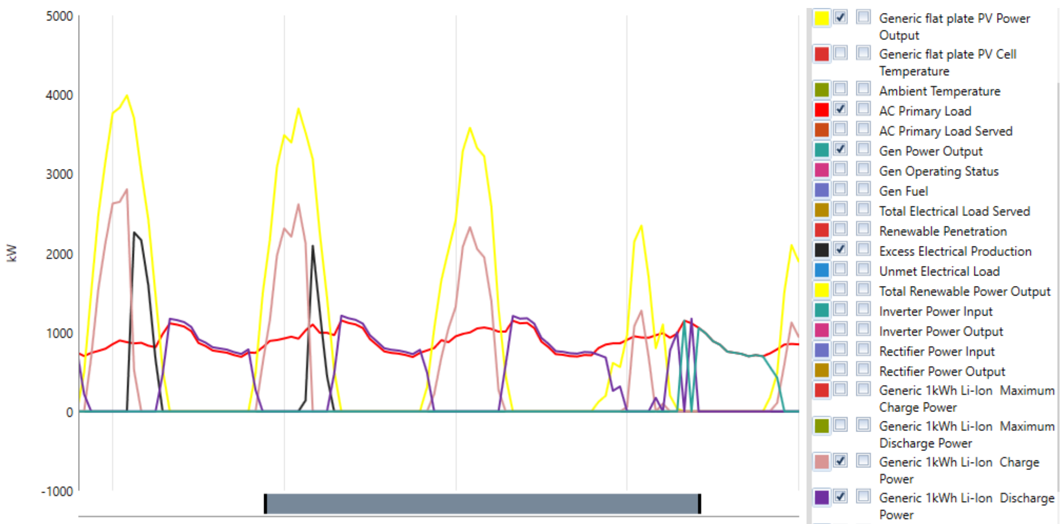



**Figure** 83: Excess in electrical production with 95 percent penetration 2020, scenario 5

### *Year 2025*

For year 2025, the results obtained can be seen in figure 85.

### *Year 2035*

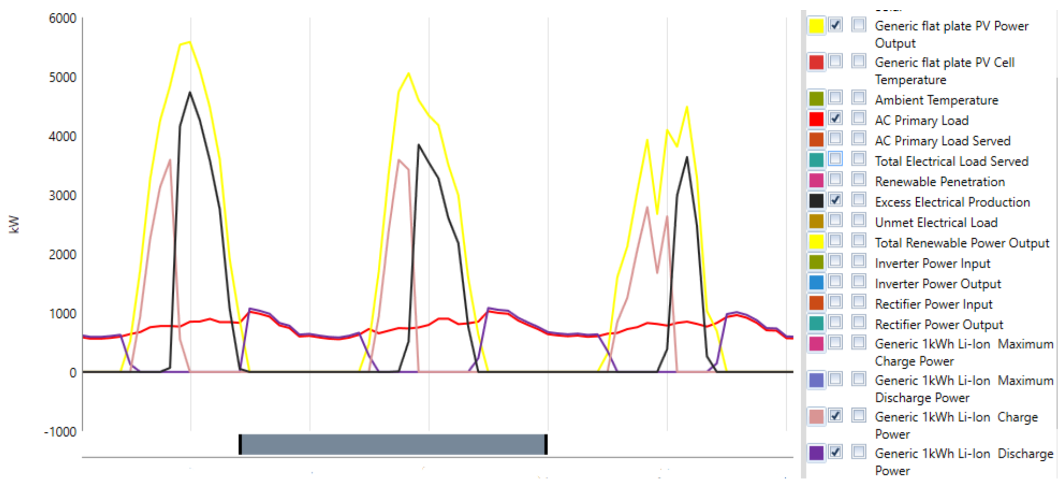



**Figure** 84: Excess in electrical production with 100 percent penetration 2020, scenaerio 5

| Architecture | | | | | Cost | | | System |
|---|---|---|---|---|---|---|---|---|
| PV (kW) | Gen (kW) | 1kWh LI | Converter (kW) | | COE (€) | NPC (€) | Initial cap (€) | Ren Frac (%) |
| 7.438 | 2.300 | 24.384 | 3.659 | LF | 0,403 € | 50,9 €M | 39,0 €M | 95,0 |
| 11.057 | | 45.000 | 5.339 | LF | 0,625 € | 78,9 €M | 61,8 €M | 100 |

**Figure** 85: Simulation results 2025 Scenario 5

Finally for year 2035, the results obatined follow the same pattern 86. In this last simulation performed the final cost of implementing a 100 % renewable project in Isabela requires an investment of 95,2 million €and the project has a cost of 120 million €, amount that can be considered economically prohibitive.

| Architecture | | | | | Cost | | | System |
|---|---|---|---|---|---|---|---|---|
| PV (kW) | Gen (kW) | 1kWh LI | Converter (kW) | | COE (€) | NPC (€) | Initial cap (€) | Ren Frac (%) |
| 11.314 | 3.400 | 35.590 | 10.391 | LF | 0,413 € | 78,2 €M | 59,8 €M | 95,0 |
| 17.586 | | 64.970 | 11.457 | LF | 0,637 € | 120 €M | 95,2 €M | 100 |

**Figure** 86: Simulation results 2035 Scenario 5

### 5.5.2. Summary and analysis of results Scenario 5

All the results of Scenario 5 are arranged in figure 87, where both possibilities, 95 % and 100 % of renewable penetration values are included in the table.

Eventhough only a 5 % of the energy in the first option comes from fossil fuels, Homer still choose generators with big capacity, although the MWh produced per year are only a few. Moreover comparing the results of both options in a same year, only a 5 % difference in renewable penetration accounts for approximately

| SUMMARY SCENARIO 5 | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| YEAR | CAPACITY INSTALLED (kW) | | ENERGY PRODUCTION (MWh) | LCOE (€/kWh) | NPC (M€) | INITIAL INV (M€) | RENEWABLE ENERGY (%) | FUEL (L) | CO2 EMISSIONS Kg/yr |
| 2015 | DIESEL | 1.100 kW | 237 | 0,389 | 24,6 | 18,7 | 95 | 68.532 | 179.390 |
| | SOLAR PV | 3.563 kW | 6.142 | | | | | | |
| | BATTERIES | 11.822 kWh, 1.447 kW | 2.657,0 | | | | | | |
| | SOLAR PV | 5.114 kW | 8.816 | 0,602 | 38,1 | 29,6 | 100 | | |
| | BATTERIES | 22.632 kWh, 2.207 kW | 2.815,0 | | | | | | |
| 2020 | DIESEL | 1.700 kW | 361 | 0,403 | 38,8 | 29,3 | 95 | 102.782 | 269.043 |
| | SOLAR PV | 5.590 kW | 9.636 | | | | | | |
| | BATTERIES | 18.306 kWh, 2.906 kW | 3.957,0 | | | | | | |
| | SOLAR PV | 8.206 kW | 14.145 | 0,624 | 59,1 | 46,2 | 100 | | |
| | BATTERIES | 34.191 kWh, 3.590 kW | 4.199,0 | | | | | | |
| 2025 | DIESEL | 2.300 kW | 485 | 0,403 | 50,9 | 39 | 95 | 137.555 | 360.065 |
| | SOLAR PV | 7.438 kW | 12.821 | | | | | | |
| | BATTERIES | 24.384 kWh, 3.659 kW | 5.267,0 | | | | | | |
| | SOLAR PV | 11.057 kW | 19.060 | 0,625 | 78,9 | 61,8 | 100 | | |
| | BATTERIES | 45.000 kWh, 5.339 kW | 5.586,0 | | | | | | |
| 2035 | DIESEL | 3.400 kW | 732 | 0,413 | 78,2 | 59,8 | 95 | 206.051 | 539.361 |
| | SOLAR PV | 11.314 kW | 19.503 | | | | | | |
| | BATTERIES | 35.590 kWh, 10.391 kW | 7.878,0 | | | | | | |
| | SOLAR PV | 17.586 kW | 30.314 | 0,637 | 120 | 95,2 | 100 | | |
| | BATTERIES | 64.970 kWh, 11.457 kW | 8.331,0 | | | | | | |

**Figure** 87: Summary of results scenario 5

50 % more in PV capacity and almost the double of batteries. This huge increase in capacity results in huge costs, around a 60 % increase in every type of cost, this is illustrated in figure 88. In the 95 % case, there is still fuel consumption and emissions to the atmosphere, however is more economically viable.89

After analysing the results a question raises: Is that 5 % difference really worth it?

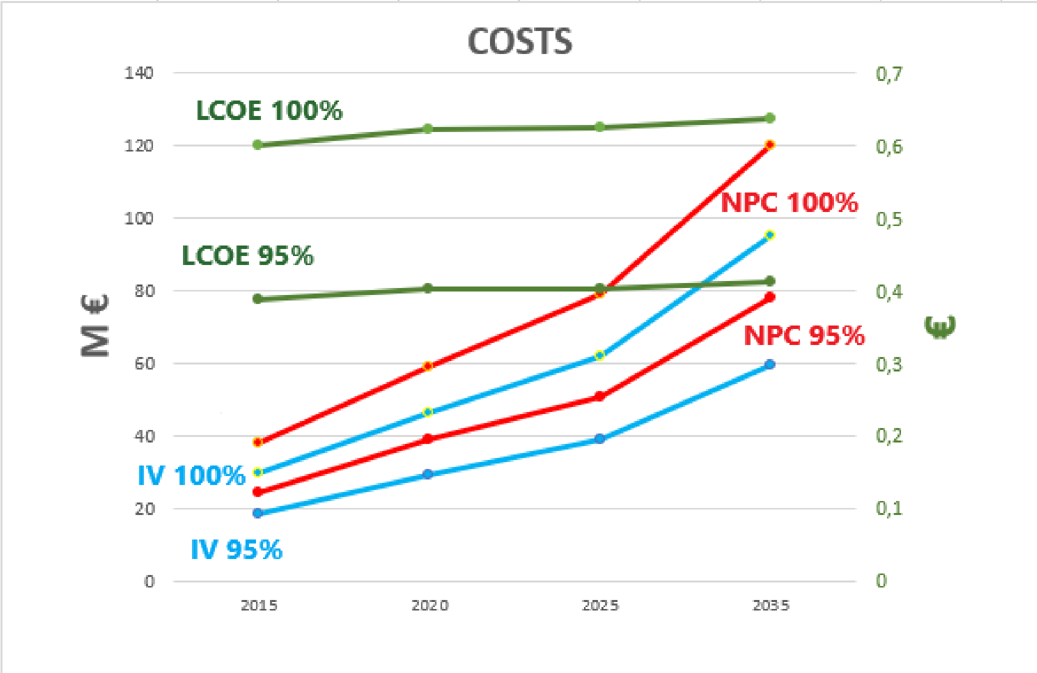



**Figure** 88: Costs Scenario 5

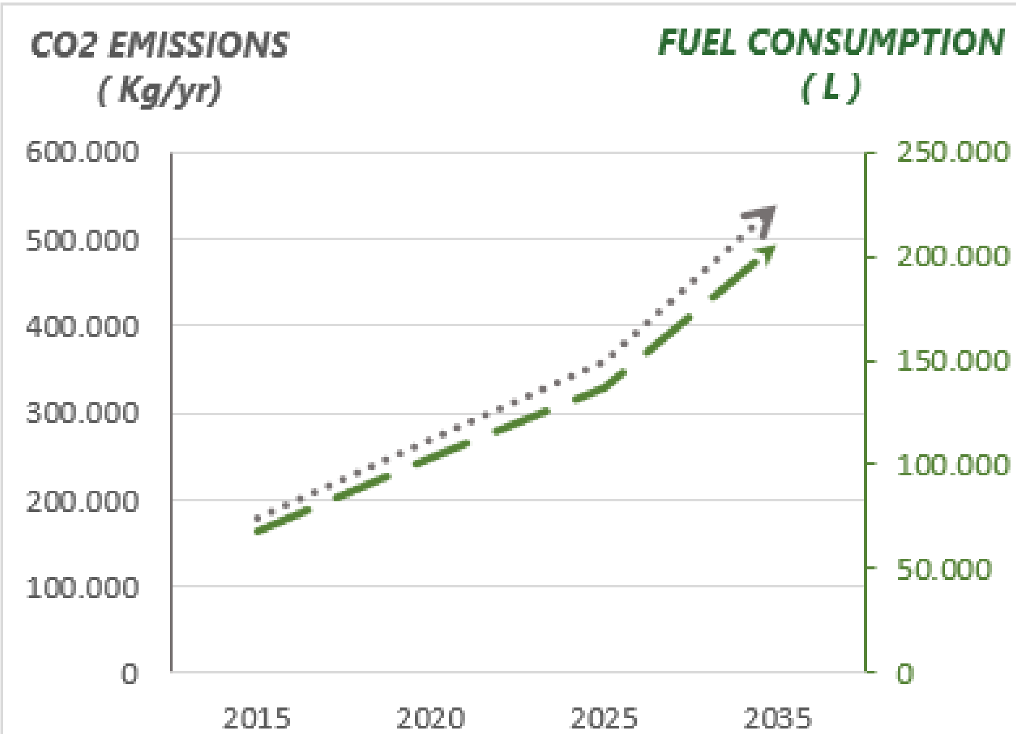



**Figure** 89: Fuel and emissions Scenario 5

# 6. Comparison of scenarios: Social, economical and environmental impacts

A comparison among all the scenarios is going to be done in this section. Graphical representations of the data shown in table 94 are used to explain the values. Although only 5 scenarios were analysed, as two different options were obtained in simulation 5, there is a total of 6 scenarios in the graphs created for this section, where the X axis show the different Scenarios ( from lower to higher renewable penetration), the different lines represent the years and the Y axis the variable compared in each graph.

In scenario 1, that corresponds to Isabela's current situation, relying completely on fossil fuels, in particular diesel, raises many issues and concerns. First of all, diesel is costly, not only the product itself but the shipment and storage costs associated. Secondly, in a small economy like Isabela's, rely completely in a fuel that is imported from other countries, makes the island susceptible to global prices fluctuations that can affect the economy. Third, fossil fuels not only pollute the atmosphere by their combustion in the generators but also can have devastating effects in an ecosystem if it is accidentally poured into the ocean, as unfortunately has happened many times throughout history. For this bachelor's thesis, a constant price of 0.8€/L is considered for the simulations, however due to lack of information, neither shipment nor storage costs are included. As Scenario 1 is only powered by generators, is the largest diesel consumer and thus the scenario where largest amounts of emissions are released. It can be seen in figures 90 and 91 that for scenario 1 values are huge and decrease throughout the scenarios as renewable penetration raises.

In the following scenarios renewable energy penetration increases gradually and brings both advantages and dissadvantages to the systems. Among the advantages, it is highlighted that fuel consumption and thus emissions, as it can be seen in the graphs 90 and 91, decrease proportionally as renewable penetration increases. Regarding year 2035, from the first to the last scenarios, there is a difference of 4 million liters of fuel and 10 million Kg of CO2. This large difference can not be disregarded cause might have many impacts, not only in the archipelago but contributing as well to global warming. Besides, natural resources are for free, therefore once the initial investment in the required technology is done, producing energy is cheap. If the price of the fuel increases considerably in the upcoming years, there is going to be a time in which the scenarios with renewable energy become more affordable than diesel's scenarios. Especially if it is taken into account that due to economies of scale and improved cost-competitiveness of renewable technologies, they are getting cheaper and cheaper.

The dissadvantages of implementing renewable energy technologies are found in the costs associated to the project. Analysing current values obtained, it is most costly to have renewable technologies than powering the system with fossil fuels. The higher the renewable capacity installed, the higher the initial investment required. The percentage of renewable penetration is more or less proportional to

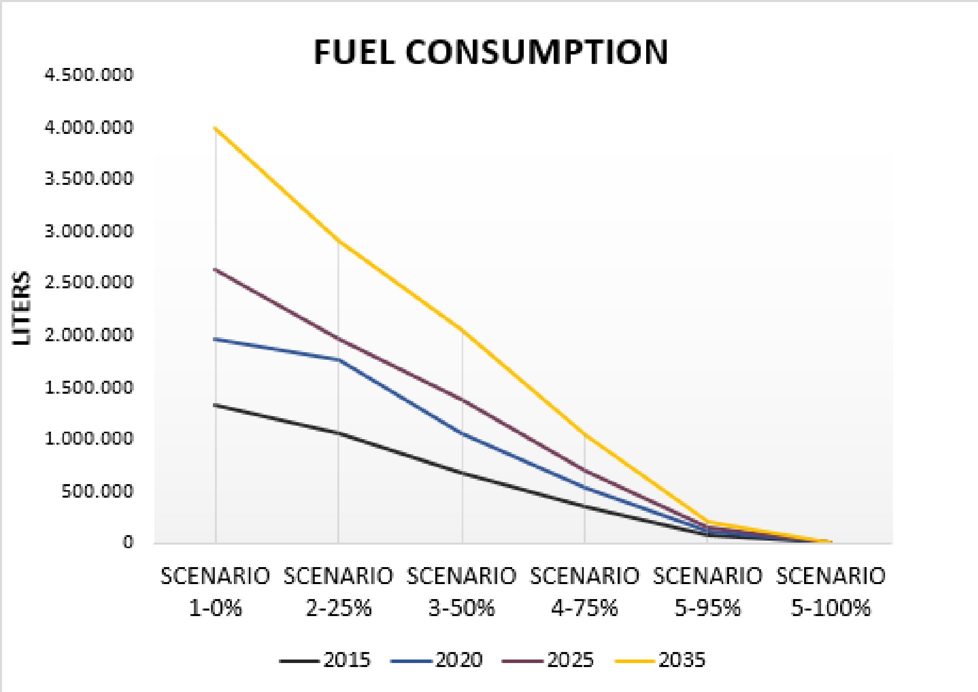



**Figure** 90: Fuel consumption comparison among all the scenarios

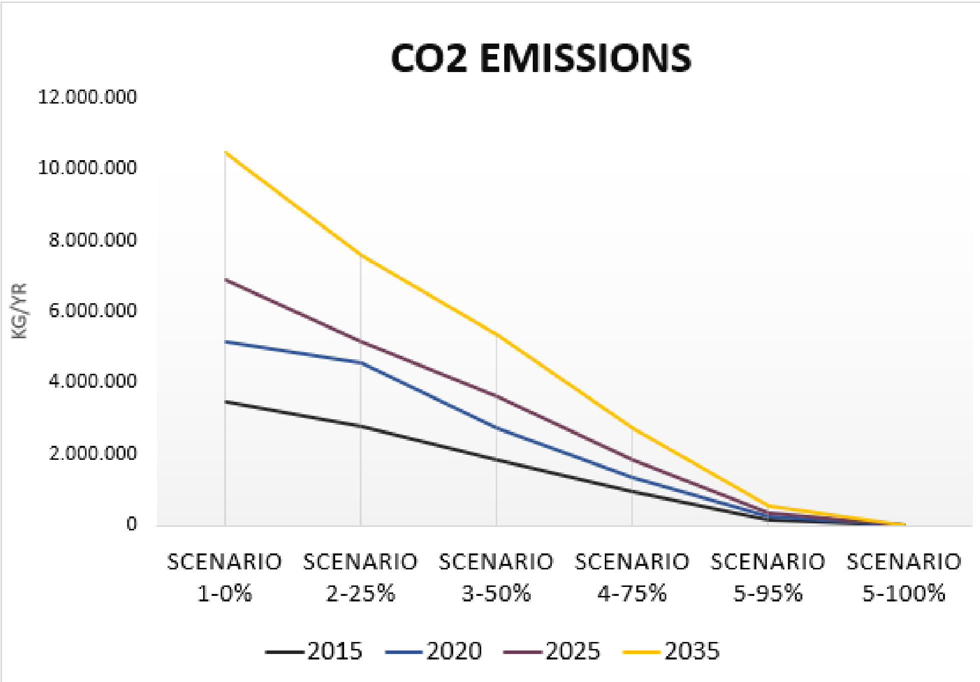



**Figure** 91: CO2 Emissions comparison among all the scenarios

the rise in the initial investment from 0 % penetration to 95 %, but it can be seen that the slopes of the curves get more pronunciated between 95 % and 100 % penetration, reaching exaggereated values. Regarding the NPC of the project, although there are variations among the different years of the study, the rise in NPC is almost proportional until 95 % is reached, beyong this point the rise is exorbitantly.

Although the cost-competitiveness of renewable technologies is rising rapidly, there are still some years left until it is economically viable to implement a 100 % renewable system. Meanwhile, surpassing 95 % of renewable penetration with the actual configuration of Isabela's hybrid system implies a huge extra installed capacity, especially of batteries, that makes the system economically prohibitive and might even have stability and shortage issues if the sun fades for few days. A possible continuation of this bachelor's thesis could be to study other suitable renewable energy technologies, storage systems or intterconnection possibilities that improve Isabela's system, lowering the prices and increasing the efficiency.

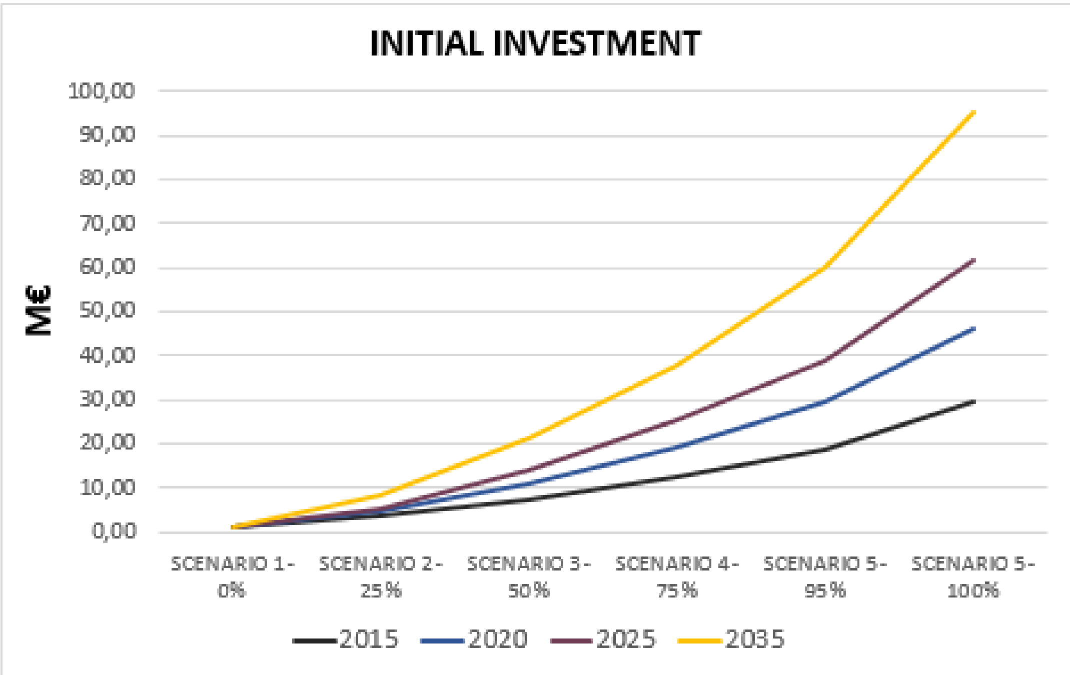



**Figure** 92: Initial Investment comparison

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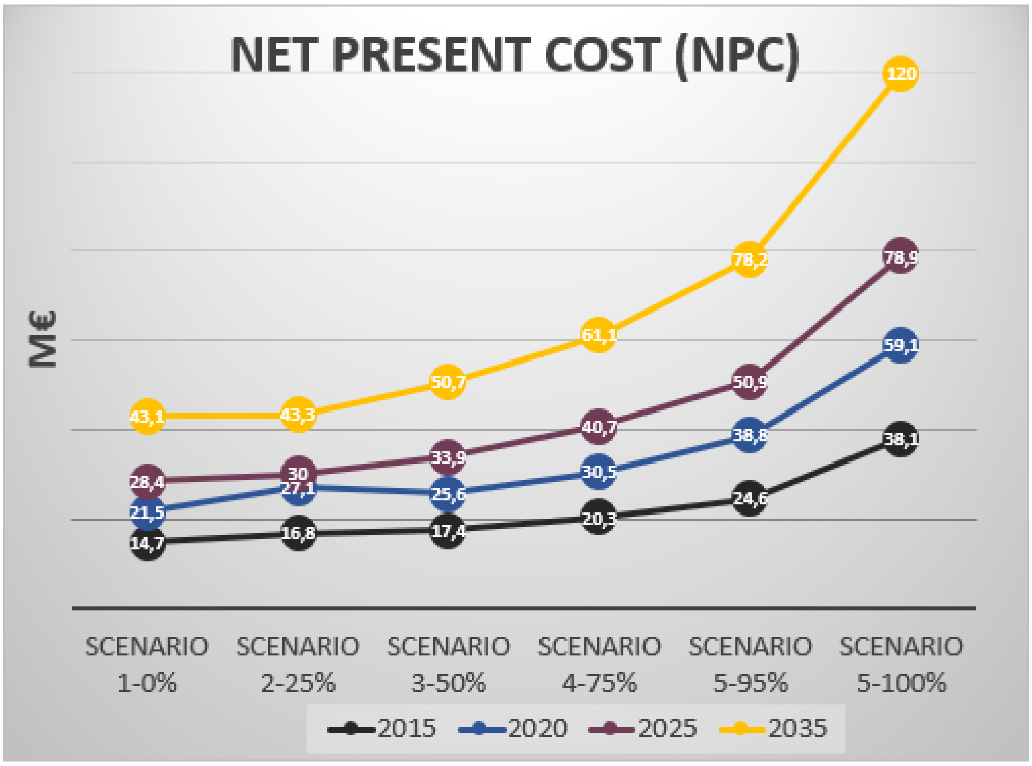


**Figure** 93: NPC Comparison among all the scenarios

| | YEAR | SCENARIO 1-0% | SCENARIO 2-25% | SCENARIO 3-50% | SCENARIO 4-75% | SCENARIO 5-95% | SCENARIO 5-100% |
|---|---|---|---|---|---|---|---|
| FUEL CONSUMP | 2015 | 1.320.143,00 | 1.059.057,00 | 669.812,00 | 353.331,00 | 68.532,00 | 0,00 |
| | 2020 | 1.963.459,00 | 1.752.721,00 | 1.042.829,00 | 520.776,00 | 102.782,00 | 0,00 |
| | 2025 | 2.623.029,00 | 1.961.721,00 | 1.381.362,00 | 694.511,00 | 137.555,00 | 0,00 |
| | 2035 | 3.980.632,00 | 2.893.336,00 | 2.053.995,00 | 1.034.209,00 | 206.051,00 | 0,00 |
| EMISSIONS | 2015 | 3.462.146 | 2.778.371 | 1.831.838 | 924.884 | 179.390 | 0,00 |
| | 2020 | 5.154.402 | 4.584.386 | 2.729.725 | 1.363.166 | 269.043 | 0,00 |
| | 2025 | 6.890.107 | 5.142.533 | 3.615.873 | 1.817.963 | 360.065 | 0,00 |
| | 2035 | 10.453.983 | 7.586.980 | 5.376.659 | 2.707.162 | 539.361 | 0,00 |
| NPC | 2015 | 14,7 | 16,8 | 17,4 | 20,3 | 24,6 | 38,1 |
| | 2020 | 21,5 | 27,1 | 25,6 | 30,5 | 38,8 | 59,1 |
| | 2025 | 28,4 | 30 | 33,9 | 40,7 | 50,9 | 78,9 |
| | 2035 | 43,1 | 43,3 | 50,7 | 61,1 | 78,2 | 120 |
| INITIAL INV | 2015 | 0,92 | 3,66 | 7,53 | 12,60 | 18,70 | 29,60 |
| | 2020 | 0,92 | 4,74 | 10,70 | 19,00 | 29,30 | 46,20 |
| | 2025 | 0,92 | 5,47 | 14,20 | 25,20 | 39,00 | 61,80 |
| | 2035 | 1,12 | 8,27 | 21,3 | 37,9 | 59,8 | 95,2 |
| LCOE | 2015 | 0,231 | 0,266 | 0,275 | 0,321 | 0,389 | 0,602 |
| | 2020 | 0,226 | 0,286 | 0,27 | 0,321 | 0,403 | 0,624 |
| | 2025 | 0,225 | 0,238 | 0,269 | 0,322 | 0,403 | 0,625 |
| | 2035 | 0,227 | 0,228 | 0,268 | 0,322 | 0,413 | 0,637 |

**Figure** 94: Summary of results for the comparison of scenarios

# 7. Conclusions

The population and tourism growth and thus the demand growth in Galapagos will require additional power capacity in the upcoming years. Galapagos is promoting decarbonization in the energy and transportation sectors, implementing renewable energy projects in the different islands and environmental policies to protect its unique ecosystem and evolve towards a sustainable future. Although Isabela is currently completely powered by diesel, this situation is about change. Analysing the different scenarios forecasted the following conclusions are obtained.

In scenario 1, where a completely non-renewable future is foreseen, although more economically accessible, would end up in millions of liters of diesel consumed and millions of kilograms of Carbon Dioxide, among many other pollutants, released to the atmosphere. This scenario could have devastating effects in the unique and privileged ecosystem of Galapagos, where thousands of animal and plant species could be affected and damaged by those huge levels of pollution. Moreover as previously stated, the economy of Galapagos Islands is based on tourism, therefore if the ecosystem is destroyed tourism levels would fall driving down the economy.

More prosperous futures appear if renewable energy is integrated in the system. As the renewable energy penetration increases, fuel consumption and emissions decrease, thus lowering the risk of fuel leaks to the ocean. Nevertheless it has to be mentioned that as renewable energy increases, the costs associated to the system, such as initial investment, the net present cost of the project and the levelized cost of energy rise considerably. This rise in costs is almost linear, around 20 % increase, until 95 % level of renewable penetration is reached, beyond this point the costs get exorbitantly high. Only a 5 % difference in renewable penetration involves a 50 % increase in the Net present cost of the project. Moreover it implies a 50 % rise in Solar PV capacity and double the capacity of the batteries, that results in prohibitive investment costs, especially for countries that are still under development.

The time frame of the grid planning performed in this bachelor's thesis is only up to year 2035, however as it is expected that the cost-competitiveness of renewable technologies and efficiency rise rapidly, in some years it will be economically viable to implement a 100 % renewable system. Meanwhile the implemantation of a renewable project in the island with a penetration level up to 95 % depens on other factors such as funds available, awareness and policies.

Environmental sensibility has a price, but its lack implies a cost.

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